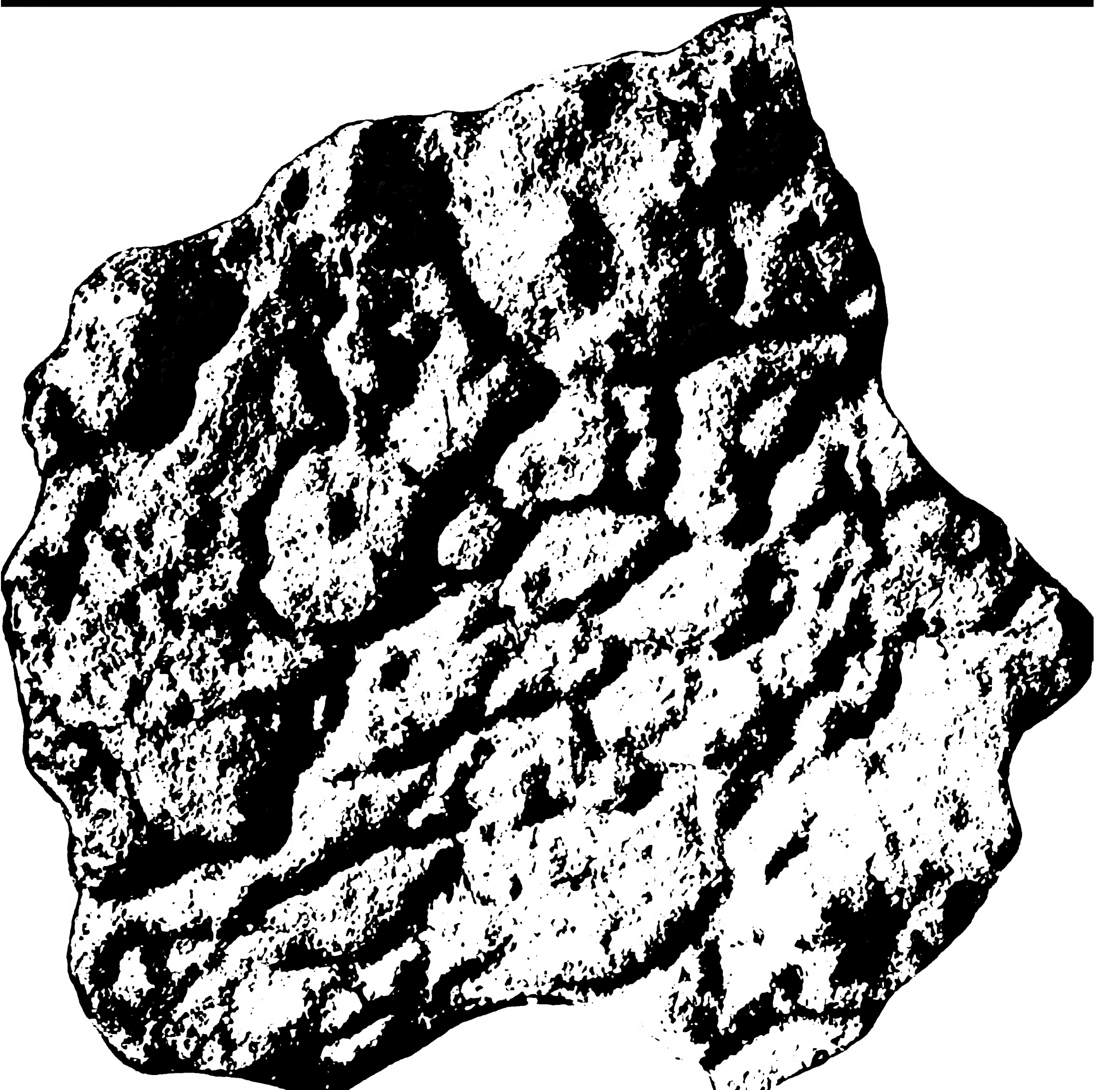

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Series { B, Descriptive Geology, 122
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DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, DIRECTOR

SUMMARY OF THE

CONTROLLING FACTORS OF ARTESIAN FLOWS

BY

MYRON L. FULLER

WASHINGTON
GOVERNMENT PRINTING OFFICE
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ILLUSTRATIONS.

SUMMARY OF THE CONTROLLING FACTORS OF ARTESIAN FLOWS.

By Myron L. Fuller.

INTRODUCTION.

Every text-book on geology and every treatise on hydraulics or hydrology discusses the occurrence of artesian waters. Unfortunately, however, only the more simple conditions are usually considered. The principle expressed by the widely prevalent maxim, "water seeks its own level," is readily grasped by every one, but it does not explain all of the features of artesian flows. That nature does not always do its work in the simplest way is recognized in all sciences, in none more generally recognized than in geology or hydrology. The ideal conditions shown in the text-books and treatises are often absent; while, on the other hand, flows occur under a great variety of conditions not commonly recognized and rarely described. The ever-present basin of popular discussions does not even predominate among the many types of artesian systems encountered in the field, and even the sloping bed is not essential. On the other hand, fissures and solution passages play very important parts, even in stratified rocks.

For these reasons and because of the present activity in artesian investigations, but more especially because of the notable change in the use of the term "artesian" since the publication in 1885 of the admirable paper of Prof. T. C. Chamberlin on the "Requisite and qualifying conditions of artesian wells,"[a] it has seemed desirable to point out certain needed modifications to the postulated requisites of flow. No attempt at exhaustive treatment is made, the aim being simply to call attention to a few of the commonly neglected elements of the problem.

In view of the number of different senses in which the term artesian has been used in the past it will not be out of place to state that in the present paper the term is applied in the sense adopted by the United States Geological Survey after consultation with

[a] Fifth Ann. Rept. U. S. Geol. Survey, 1885, pp. 125–173.

leading geologists of the country, namely, to designate the hydrostatic principle by which confined waters tend to rise in virtue of the pressure of the overlying water column, whether or not this pressure is sufficient to lift the water to the surface and produce a flow.[a]

UNDERGROUND CONDITIONS.

Preliminary to the discussion of the essential factors of artesian flow, a résumé of the geologic conditions affecting artesian waters is desirable. The following paragraphs present some of the factors bearing on the occurrence and movements of such waters.

UNDERGROUND RESERVOIRS.

TYPES.

By "underground reservoir" is meant the opening or system of openings in which underground water is contained. It is needless to say that, except an occasional cavern of very limited extent, such reservoirs bear no relation to open basins of the surface type, but are most of them rock strata or masses in which the only openings are spaces between the grains or along lines of solution or of jointing, cleavage, bedding, or other structure planes or fissures. Among the various types of reservoirs the following are the most important water producers:

Types of underground reservoirs.

- I. Original forms.
  - A. Original pores.
  - B. Lamination planes.
  - C. Bedding planes.
  - D. Vesicles (in igneous rocks only).
- II. Secondary forms.
  - A. Secondary pores.
    - 1. Pores resulting from leaching and solution.
    - 2. Pores resulting from recrystallization.
  - B. Solution openings.
    - 1. Isolated cavities.
    - 2. Tubular channels.
    - 3. Sheet openings.
  - C. Mechanically eroded reservoirs.
    - 1. Tubular channels.
    - 2. Pocket openings.
    - 3. Sheet openings.
  - D. Fracture openings.
    - 1. Irregular openings.
      - a. Desiccation cracks.
      - b. Contraction fissures.

[a] Fuller, M. L., Significance of the term "artesian:" Water-Sup. and Irr. Paper No. 160, U. S. Geol. Survey, 1906, pp. 9–15.

II. Secondary forms—Continued.
- D. Fracture openings—Continued.
  - 1. Irregular openings—Continued.
    - c. Torsion fractures.
    - d. Shearing breaks.
    - e. Vibration fractures.
    - f. Explosion ruptures.
  - 2. Joints.
    - a. Vertical joints.
    - b. Horizontal joints.
    - c. Parallel joints.
    - d. Intersecting joints.
    - e. Joint breccias.
  - 3. Faults.
    - a. Single fault planes.
    - b. Parallel fault planes.
    - c. Irregular faults.
    - d. Intersecting faults.
    - e. Fault breccias.
  - 4. Vein contacts.
  - 5. Igneous contacts.
  - 6. Shearing planes.
- E. Cleavage planes.
- F. Foliation and schistosity planes.

Most of the forms enumerated are not limited to any particular class of rock, but may be found in the stratified, metamorphic, and igneous types. The vesicles of igneous rocks, however, have no exact counterpart in stratified rocks, although the pores containing included water of sedimentation approach them in nature. Solution channels are likewise usually, although not necessarily, found only in sedimentary rocks; foliation and schistosity are mainly features of igneous or metamorphic rocks, while lamination, as the term is here used, is a feature of stratified rocks.

ORIGINAL FORMS.

Original pores.—The original pores include both the pores of the primary rocks and the unfilled spaces between the fragments or grains of the fragmental and other secondary rocks, including till, sand, and gravel; sandstone and conglomerate; oolite, shell limestones, chalk, etc. The minute pores in clays, as well as the intercrystal spaces resulting from the contraction and adjustment incident to the cooling of igneous rocks, belong in this class, although these are usually far less important than the macroscopic pores of the coarser sedimentary rocks. The original pores rank first in water-bearing capacity, characterizing all of the best-known types of water beds.

Lamination planes.—Lamination planes, or the crowded partings which separate certain of the finer stratified rocks into numberless thin sheets or laminæ parallel to the bedding, are of considerable im-

portance. Many shales, especially where the partings have been somewhat opened by the weather near the surface, carry large amounts of water in such planes. The general exudation of water from laminated beds, such as often occurs throughout a considerable vertical range where the layers are exposed in cliffs or in the artificial faces of quarries, is familiar to everyone.

Bedding planes.—Bedding planes, or the partings between individual layers or beds of the same or different classes of rock, often carry large amounts of water. This is in part due to the fact that the adhesion along such planes is less than that in a mass of homogeneous material, a condition which results largely from the imperfect contact due to variations of material, changes in texture, variations in arrangement, etc., which have resulted from changes or halts in deposition. This lack of adhesion makes the bedding planes more readily available for the passage of water than the body of the rock. Difference in permeability of the overlying and underlying layers is also a leading factor in the concentration of water along the bedding planes, making the latter, next to the original pores, the most important water containers. This is especially true where the planes have been somewhat widened by subsequent solution admitting the free passage of water, as shown in Pl. I, *A*.

Vesicles.—Vesicles, or cavities resulting from the expansion of steam in cooling lavas, form a distinct although not a common type of reservoir. Usually the vesicles are very imperfectly connected, but in some of the Newark lavas, such as have been described by B. K. Emerson and others, the vesicular portions of the trap seem to form a definite water horizon. The same is doubtless true of many other scoriaceous lavas, both those occurring on the surface and those buried beneath subsequent deposits. The possibility of a general water movement through such materials is shown by their secondary mineralization, seen in both mines and surface exposures. The almost universal mineralization of the upper vesicular portions of the copper-bearing traps—the amgydaloids—of Keeweenaw Point, Lake Superior, is a particularly good illustration of deep-seated movements in such zones.

In the same class with the vesicles, though of different origin, may be placed the cavities due to contraction of igneous magmas on cooling, especially magmas of the acid type. Original, crystal-lined openings up to 3 feet in diameter have been noted by the writer in the pegmatites of New Hampshire, and minute cavities exist in many other rocks. While rarely important as containers of water, they are, nevertheless, of sufficiently common occurrence to necessitate their inclusion with the other possible reservoirs.

A. THE BEDDING PLANE; SPRING EMERGING FROM BEDDING PLANE IN LIMESTONE.

B. RAMIFYING CHANNELS ALONG BEDDING PLANE IN LIMESTONE.

ARTESIAN RESERVOIRS.

SECONDARY FORMS.

Secondary pores.—By secondary pores are meant those minute spaces—too small to be designated as openings or cavities—which have resulted from the processes of weathering, solution, recrystallization, etc. Many of these are of much importance. The dolomitized portion of the Trenton limestone in parts of Ohio and Indiana, for instance, is sufficiently porous to carry considerable volumes of water; the original cement has been removed from calcareous sandstones in many areas, leaving them open and porous; soluble minerals, such as pyrite and calcite, are here and there leached from their relatively insoluble matrix, leaving notable open spaces; and the grains of crystalline rocks become so loosened by weathering for a depth of many feet that the material absorbs water almost like a sponge. It is doubtless through the formation of secondary pores that circulation is established along many of the lamination and bedding planes, leading eventually to the formation of open solution passages.

Solution openings.—These are among the most important of the secondary reservoirs and, as their name implies, are formed by the solvent action of percolating waters. They may be divided for convenience into (1) isolated irregular or roughly spherical reservoirs and (2) elongated passages or channels of tubular or sheet form.

The first of these types, at least where not connected with other passages, seems to be of rare occurrence. Many geodes, however, showing horizontally banded fillings, occur in the body of limestones without connection with recognizable openings through which the mineralized solutions could have entered, the spaces apparently being first dissolved and then gradually filled by water entering through the pores of the body of the rock. It is not impossible that some of the ore pockets in certain limestones may be of this origin, although by far the greater part of these seem to be direct replacements.

Of the elongated passages or channels, the ordinary caves are the best examples (Pl. II, *B*). Some of them are of great length, a single passage in the Mammoth Cave of Kentucky being over 8 miles long. Many such passages are 20 feet high; a few are as high as 75 feet; and some are as much as 50 to 150 feet wide. Some of the chambers which have been penetrated by mining shafts have shown hardly a trace of the openings through which the water entered or passed out, the openings simulating on a large scale the geode cavities described. The great vertical wells of the Mammoth and other caves, having diameters of 10 feet or more and depths of more than 200 feet, and the similar "natural wells" of Florida and elsewhere also belong to this class.

Many of the channels of this type have resulted from the enlargement of joints, the action being especially marked near the intersection of two or more planes, the great irregularity of some of the openings being accounted for by the complexity of the joint or fracture systems. This appears to be the case in the Joplin zinc district. Elsewhere, however, many of the largest passages follow bedding planes without reference to jointing, apparently having developed from one of the many meandering and branching passages that characterize such planes at many points. A view showing a network of small channels on one of these bedding planes is reproduced as Pl. I, *B*. The small channels are gradually enlarged and tend to coalesce and form a single large channel which, by continued solution, is gradually widened until a cave results. A few small tubular channels that pass diagonally through the rock without apparent connection with joints or bedding planes have been noted. The determining causes of such passages are not known, but it seems certain they represent simply the enlargements of some preexisting line of easy water movement.

The sheet form of solution passage is the first stage in the enlargement of joints, faults, or other planes. The secondary pores first formed eventually unite into an exceedingly narrow sheet-like opening. In crystalline and other insoluble rocks these may persist indefinitely, but in limestones differential solution soon develops the characteristic irregular cavities.

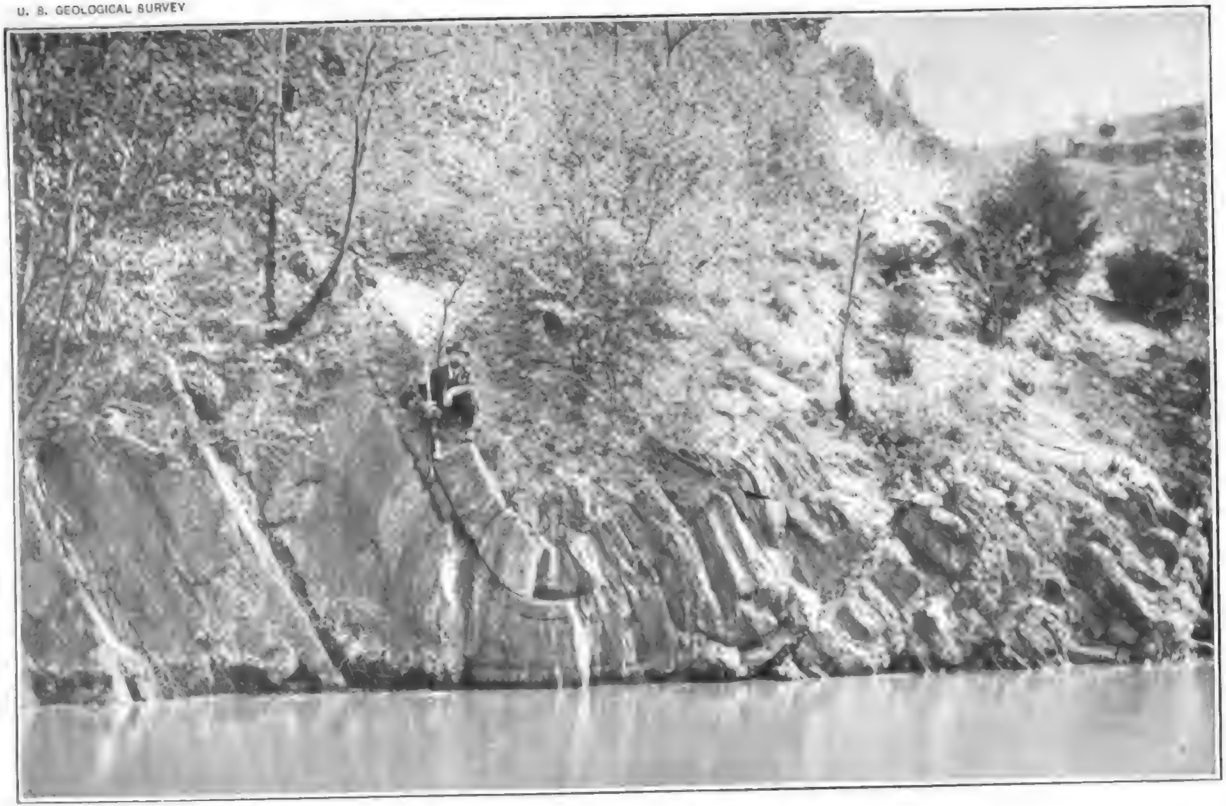
Mechanically formed reservoirs.—These include (1) irregular, but usually more or less tubular passages, many of which are followed by waters, in clay, till, and similar materials, and (2) certain of the water-bearing gravel pockets. The former may frequently be examined in detail where springs emerge from bluffs. In general they are from 1 to 4 inches in diameter, although larger ones doubtless occur, and are probably of considerable length. Their manner of formation is very similar to that of the limestone passages, except that the action is mechanical instead of chemical. The water finds its way along some bedding, joint, or other plane, gradually picking up and carrying away, particle by particle, the fine material with which it comes in contact until an open passage finally results.

Allied to these passages in manner of formation are the gravel pockets in till. Flowing wells from tills have been known to bring up cartload after cartload of clay and fine sand, until the original mixture of clay and pebbles about the well has given place to a loose and open gravel. Similar pockets appear to have been formed in many places by natural circulation, where springs have broken through till deposits, and extensive layers of gravel are believed to have been produced where general movements have occurred along lamination partings within the till.

A. EARTHQUAKE CRACK FILLED WITH SAND DIKE, BETWEEN WALLS OF CLAY.

B. UNDERGROUND SOLUTION CHANNEL.

ARTESIAN RESERVOIRS.



ARTESIAN RESERVOIRS; TORSION CRACKS DUE TO FOLDING.

Fracture openings.—Under this head are included a number of openings of varying character, due to a wide range of causes. Joints and irregular fissures are the most common types and may be classed—according to the presence or absence of movement of the walls—as simple or fault openings.

The immediate cause of all such openings is probably local tension, although compression is frequently the indirect cause. Fractures resulting from the contraction of the rocks accompanying cooling, dehydration, etc., are caused solely by tension, but in expansion or dilation due to hydration, etc., the local tension giving rise to the fractures is simply an incidental result of the pressure resulting from the expansion. Similarly, the so-called compression fissures or cracks formed in a rock cube subjected to heavy pressure, while resulting from the compression of the block as a whole, are in themselves due rather to local tension developed as a result of readjustments under the influence of the pressure. Again, in the case of rock folds, although pressure produces the arching, it is the tension developed by the bending that actually produces the fractures (Pl. III). For convenience of discussion fracture openings are here divided into irregular openings, joints, faults, and igneous and vein contacts.

Irregular openings.—In this class are included several types of openings, such as the intersecting cracks formed by the dessication of wet silts, the fractures resulting from the contraction of igneous rocks on cooling, the breaks arising from the distortion of beds in folding, the gashes produced in the adjacent rock mass by the drag incident to faulting or by the movements accompanying expansion by hydration, the cracks caused by earthquake waves in soft materials (Pl. II, *A*), and possibly certain profound fractures due to the general cooling of the earth's crust. In the same class should probably be placed the irregular but more or less circular openings connecting with surface "craterlets," formed by the occasional expulsion of gas[a] arising from the decay of woody matter in unconsolidated formations and by the expulsion of water through the body of the soil (not through the cracks) in time of earthquakes.[b]

Openings of the types outlined are of common occurrence and wide distribution, but in the main are of small size. Occasionally, however, even where there has been no faulting, they are, as attested by fissure veins, of considerable width and have afforded passages for immense volumes of water.

Joints.—For the purpose of this discussion the details of the origin of joints need not be considered, and they may be simply defined as

[a] Shaler, N. S., Conditions and effects of the expulsion of gases from the earth: Proc. Boston Soc. Nat. Hist., vol. 27, 1896, pp. 89–196.

[b] Dutton, C. E., The Charleston earthquake of August 31, 1886: Ninth Ann. Rept. U. S. Geol. Survey, 1889, pp. 203–328.

smooth fracture planes cutting the rock in various directions, but unaccompanied by any differential movement of the walls. Joints vary in position from vertical to horizontal, but commonly make an angle of 70° or more with the horizon. The spacing also varies greatly according to the character of the rock and the disturbance to which it has been subjected, but on the whole the spaces between joints are greatest in sandstones and similar rocks and smallest in slates. In the latter rock it is not infrequent to find, on the one hand, zones broken up by parallel joints into thin sheets (Pl. IV) and, on the other hand, zones cut up by intersecting joints into minute rhombs, converting the mass into what may be termed joint breccias (Pl. V, *B*). An investigation of the granites of Connecticut made by Mr. E. E. Ellis[a] showed that the spacing of the vertical joints at the surface commonly ranged between 3 and 7 feet, while the horizontal joints varied from an average of 1 foot apart in the upper 20 feet of rock to 6 to 30 feet apart in the succeeding 80 feet (Pl. V, *A*). The width of the openings varied from 2 inches at the surface to a fraction of a millimeter at depths of 25 to 100 feet.

Notwithstanding the narrowness of the joint openings, experience in mining regions and in quarries has shown the existence of connecting systems extending over large areas. At Cripple Creek, for instance, as described by Lindgren and Ransome,[b] the system of connecting joints extends over an area 3 miles in diameter and is so open that the entire tract might be drained from a single point. The volume of water held in such a system is enormous and its removal by pumping often entails great expense to the mines. Quarries also frequently have trouble with water, and heavy pumps must sometimes be installed to remove it. In general the circulation in vertical joints is much greater than in horizontal joints, water being especially abundant where two or more fractures of the former type intersect.

Vein contacts.—Many of the contacts of veins with their wall rocks are characterized by extensive circulation of water, which, like the waters in joints, often interferes seriously with mining and adds greatly to its cost. In general, however, the passages are very small, the water following, at least at first, the almost inappreciable openings along the walls, where, as along many bedding planes, the water finds access because of the imperfect nature of the contact between unlike materials In true veins the original fracture is probably most commonly a joint plane, but deep irregular fissures are not uncommon. In segregation veins the contacts may be regarded as solution surfaces.

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[a] Ellis, E. E., Occurrence of water in crystalline rocks: Water-Sup. and Irr. Paper No. 160, U. S. Geol. Survey, 1906, pp. 19–28.

[b] Lindgren, Waldemar, and Ransome, F. L., Report of progress in the geological resurvey of the Cripple Creek district, Colorado: Bull. U. S. Geol. Survey No. 254, 1904, pp. 31–32.

ARTESIAN RESERVOIRS; SHEET JOINTING.

A. HORIZONTAL JOINTS IN GRANITE

B. JOINT AND FAULT BRECCIA.

ARTESIAN RESERVOIRS.

Igneous contacts.—What has been said of the vein contacts applies with equal force to the igneous contacts of the dikes or sills intruded into joints, bedding planes, or other preexisting fractures or lines of separation. In some places igneous masses, as certain acid pegmatites, have actually eaten their way into the country rock, and the contacts often have no relation to previous structures. They are, however, less likely to afford favorable conditions for the circulation of water than the contacts of the normal type.

Faults.—Although faults are far less numerous than joints, they are more likely to be associated with extensive circulation systems than the latter (Pl. VI, *A*). This, in large measure, is the result of the movement of the walls by which opposing projections are brought opposite one another, leaving intervening openings along which the water freely circulates. Sheeted zones, with large numbers of closely adjacent parallel fault planes, and crushed zones or fault breccias, are also common, and likewise afford exceptionally good water passages and reservoirs (Pl. VI, *B*).

Shearing planes.—Shearing is closely allied to faulting, inasmuch as it implies a differential movement of adjacent portions of the rock, but differs from faulting in that it usually comprises no lines of definite fracture, but consists rather of a readjustment of the material along parallel planes throughout the rock. At the start there are no actual openings, but the shearing planes are lines of weakness and are more or less permeable to water, and, when near the surface, rapidly widen into material openings under the influence of the weather, often becoming reservoirs of importance.

Cleavage planes.—These are more or less vertical planes, produced by the action of pressure, etc., on certain compact rocks such as slate. Unlike most joints, they are not ordinarily actual fracture planes, but are simply lines along which the rock tends to split under favorable conditions. It is not probable that they carry much water when at a depth, but near the surface, where they have been somewhat opened by the agencies of weathering, considerable quantities are frequently stored in them (Pl. VII, *B*).

Foliation and schistosity planes.—These planes, dependent upon the parallel arrangement of the crystalline components of igneous or metamorphic rocks, are similar in many ways to the shearing and cleavage planes, being potential rather than actual rifts, but under the action of the weather appreciable openings holding considerable quantities of water soon develop. Some weathered schists appear to hold 15 per cent or more of their bulk of water (Pl. VII, *A*).

SOURCES OF UNDERGROUND WATER.

The probable source of underground waters has been widely discussed, and while everyone would doubtless agree that by far the

greater part is derived from rainfall there is a considerable variation of opinion as to the relative importance of the other sources, especially as to the part played by the sea and aqueous magmatic emanations. The common sources of underground waters are given below:

Sources of underground waters.

I. Atmosphere.
 1. Direct.
  a. Precipitation.
  b. Condensation.
 2. Indirect.
  a. Lakes.
  b. Streams.
II. Hydrosphere, or ocean.
 1. Contemporaneously absorbed waters.
 2. Originally included sea water.
III. Lithosphere, or crust.[a]
 1. Primary waters.
  a. Chemically excluded waters.
 2. Secondary waters.
  a. Physically excluded waters.
IV. Centrosphere, or interior.[a]
 1. Waters directly excluded.
 2. Indirectly excluded magmatic waters.

WATERS FROM THE ATMOSPHERE.

Precipitation and condensation.—Water from the atmosphere, aside from the amount entering immediately into chemical combination with surface materials, reaches the surface rocks either by precipitation or condensation. The following outline illustrates the disposal of the waters.

Disposal of precipitation.

I. Direct evaporation before absorption or run-off.
 a. Evaporation of the water film from soil and rock surfaces, vegetation, etc.
 b. Evaporation from undrained pools.
 c. Evaporation from snow surfaces.
II. Absorption by vegetation.
 a. Living.
 b. Vegetable mold, etc.
III. Direct run-off (without previous absorption).
IV. Absorption by soils and rocks.

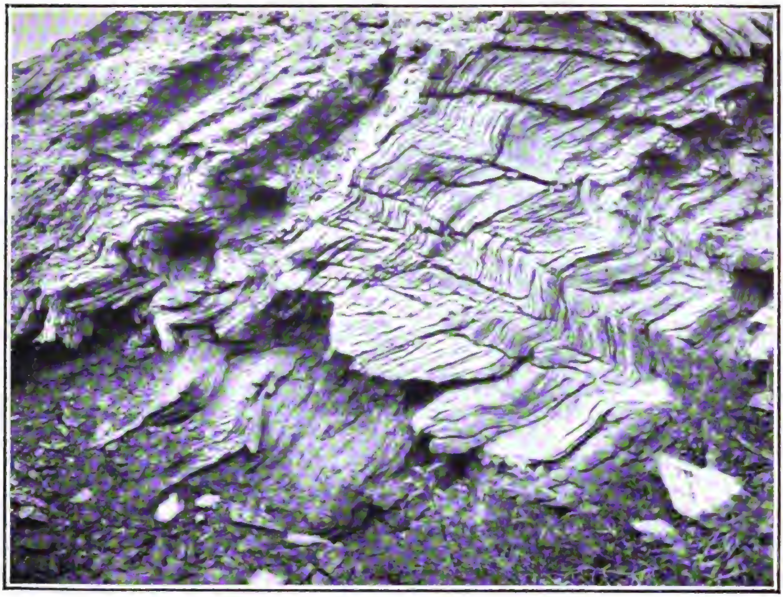
The relative importance of the several methods of disposal will vary greatly according to temperature, humidity, vegetation, character of soils, and other related factors. In humid regions and with soils of average porosity the absorption by rocks and soils is by far

[a] These terms are used as defined by J. W. Powell, Mon. Nat. Geog. Soc., vol. 1, No. 1, 1895, p. 1.

A. SOLUTION CHANNEL ON FAULT LINE.

B. CRUSHED ZONE ON FAULT.

ARTESIAN RESERVOIRS.



A. SCHISTOSITY PLANES.

B. CLEAVAGE PLANES.

ARTESIAN RESERVOIRS.

the most important, probably accounting for at least 85 per cent of the precipitation. In certain sandy regions, as on Cape Cod, Long Island, it is probable that nearly or quite 95 per cent of the water enters the soil immediately, there being practically no direct run-off except on the rare occasions when rain falls on frozen ground or snow. In clayey regions and in areas of rock, especially where vegetation is very scarce, a large local and temporary run-off may result.

Any surplus of the water of condensation over that required to wet the surface of the ground and vegetation is taken up directly by the soil, there being practically no evaporation under the existing conditions. Ordinarily the amount so derived is small, but it may become of some consequence in certain mountainous regions, where direct condensation is sometimes sufficient to form little rivulets of water on the condensing surfaces.

Waters from lakes and streams.—One of the most common popular conceptions is that ground waters are derived either from neighboring or more remote lakes and streams. It is too well known to require more than the simple statement, however, that the movement of such water is normally toward and not away from the water bodies, the surfaces of which are below and not above the water table. It is only when there is some sudden rise of water in the lake or stream due to causes independent of local rainfall that the level becomes higher than the adjacent water table and a landward movement takes place. These conditions are illustrated by fig. 1. Such movements occur tempo-

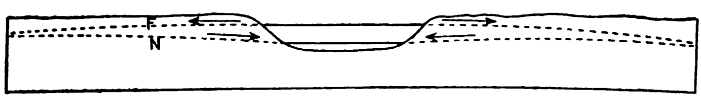


FIG. 1.—Section illustrating conditions governing movement of water away from streams or lakes. N, Normal position of water table; F, position of water table during floods.

rarily during the flood period of rivers fed from mountain snows, etc., or in lakes supplied by such streams. Similar conditions exist where the torrents resulting from cloudbursts temporarily flood certain parts of our great deserts.

WATERS FROM THE OCEAN.

Contemporaneous absorption.—As in the case of rivers and lakes, the ground-water movement is ordinarily toward the sea, but occasionally, especially in estuaries, severe storms bank up the waters to a height of several feet above their normal level for a considerable length of time. At such times movements of salt water into the sand may occur, sometimes seriously affecting adjacent shallow wells.

Other than under the above conditions, ocean water does not commonly penetrate inland. When the natural conditions are disturbed however, as when wells near the shore are heavily pumped, the water table may be sufficiently lowered to establish a reversed movement. Salt water also occasionally penetrates far inland where open solution channels in limestones—now abandoned by the streams which formed them—afford passages for it. Probably the most remarkable case of penetration by sea water is that at the so-called Sea Mills of Cephalonia in Greece, where a steady stream large enough to run a mill has from time immemorial left the sea and passed inland, finally disappearing into the porous limestone.[a]

The supposed causes of this phenomenon are discussed on page 30.

Originally included sea water.—Sediments formed in the ocean include large quantities of sea water, the amount varying from 10 to 40 per cent or more of the bulk of the material according to its nature. Ordinary sands commonly hold about one-third of their volume. If the marine beds are lifted above sea level while still in an unconsolidated condition much of this water will drain out except when the beds are so warped in the process as to form troughs or when drainage is prevented by the presence of overlying impervious beds.

The Cretaceous deposits near Wilmington, N. C., afford a good example of included waters in beds not yet uplifted, flowing wells of salt water being obtained at many points, even beneath impervious clays which effectually prevent any present access of the sea water. The pressure comes from the meteoric waters entering at the outcrop near the inner edge of the Coastal Plain, and as the salt water is removed fresh water takes its place. Instances of salt wells turning fresh have been described by the writer in another paper.[b] Perhaps the best illustration of included water in older and uplifted rocks is that afforded by the salt waters of the thick, open sandstones of the Carboniferous series of western Pennsylvania, the waters occurring under conditions which seem to preclude their access to any salt-bearing beds.

WATERS FROM THE ROCKS OF THE CRUST.

By waters from the lithosphere or crust are meant the originally combined or otherwise unavailable waters which have later been set free by physical or chemical exclusion. In their original form the waters are either primary (forming a part of the original minerals) or secondary (derived from absorption by some one of the methods outlined in the preceding sections).

[a] Crosby, F. W., and Crosby, W. O., The Sea Mills of Cephalonia: Tech. Quart., vol. 9, 1896, pp. 6–23. Fuller, M. L., Bull. Geol. Soc. America, vol. 18, pp. 221–232.

[b] Fuller, M. L., Instances of improvement of water in wells: Water-Sup. and Irr. Paper No. 160, U. S. Geol. Survey, 1906, pp. 96–99.

Chemically excluded waters.—The chemically excluded waters are the originally combined waters which have been set free by chemical processes. As first formed numerous minerals are in the hydrated form, but later, usually through the influence of heat and pressure, lose the whole or part of their water. This process of dehydration commonly takes place only at considerable depths, and usually results from recrystallization or recombination due to metamorphism. In some cases the entire amount of water contained by the minerals is excluded, but in others, as in some of the recombinations, only a part is driven out. Among the best illustrations of the processes are the exclusion of mechanically included waters by the crystallization of amorphous limestones as calcite, by the change of certain gypsums through metamorphic action to anhydrite, and by the change of peat and lignite to coal. The action is not solely deep seated, there being more or less extensive dehydration, especially of iron compounds, in regions where hot and dry seasons alternate with periods of rainfall. Van Hise attributes the red hematitic stains, colorings, etc., of the deserts of southern California and elsewhere to the dehydration of the iron from the limonite form.[a]

Since dehydration takes place mainly at considerable depths the water is not lost to the rock crust as a whole, but simply to the part undergoing alteration. Most of it passes upward into the more porous unaltered rocks, in which it may remain for an indefinite period.

Physically excluded waters.—The expulsion of secondary waters, including those derived from the process of dehydration in underlying rocks in the manner just described, as well as the included "waters of deposition," occurs mainly through the agency of pressure and heat. The exclusion by pressure is well illustrated by the violent expulsion of water along fault rifts during great earthquakes, an action which, although especially manifest at the surface, can hardly be confined to this zone, but must often occur between beds at considerable depths. The action of heat in expulsion will be most pronounced where water-bearing strata are penetrated by igneous intrusions, especially where ready escape for the steam or water into overlying beds is afforded by joint, fault, or other openings.

WATERS FROM THE CENTROSPHERE.

The waters from the centrosphere may be divided into those reaching the reservoirs in the crust by direct emanation or exclusion, and those reaching the upper crust indirectly through igneous intrusions. As was shown by Hoskins,[b] rock pressure limits the occurrence of open

[a] Van Hise, C. R., Some principles controlling the deposition of ores: Trans. Am. Inst. Min. Eng., vol. 30, 1900, pp. 27–177.

[b] Hoskins, L. M., Flow and fracture of rocks as related to structure: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845–875.

cavities in ordinary rocks to depths under 10,350 meters, but rock-inclosed, liquid-filled cavities can exist to an indefinite depth at which water and molten rock are miscible in all proportions. The volume of aqueous matter in the central magma is an unknown quantity, but it is acknowledged that practically all lavas contain material amounts of water, and while some, if not most of it, may be derived from the rocks through which the lavas have passed, a part is doubtless derived from the original magma. It is not improbable that as the cooling of the central magma progresses considerable amounts of water are given off into the overlying rocks. This and the more common form of magmatic waters—that given off from igneous intrusions—together form, in the belief of many geologists interested in economic deposits, an important source of ore-depositing solutions. At any rate it may safely be said that it is often of great local importance.

CONFINING AGENTS.

In this discussion the confining agents in artesian systems are divided for convenience into bedded and jointed rocks. In the usual discussion impervious beds are ordinarily the only agents recognized, but observations made by a considerable body of field workers during the last four years has brought to light some new conditions of flow and has emphasized the importance of a number of factors that are seldom mentioned. The principal confining agents are as follows:

Confining agents.

I. Bedded rocks.
- A. Upper confining agents.
  1. Impervious beds.
  2. Stratification.
  3. Friction.
  4. Mineral crusts.
  5. Frost zones.
  6. Confined air and gas.
  7. Fresh water.
  8. Salt water.
- B. Lower confining agents.
  1. Impervious beds.
  2. Stratification.
  3. Friction.
  4. Mineral crusts.
  5. Frost zones.
  6. Confined air and gas.
  7. Fresh water.
  8. Salt water.
  9. Cementation.
  10. Heat.
  11. Pressure.

II. Jointed and fractured rocks.
  A. Upper confining agents.
    1. Impervious hanging wall.
    2. Impervious surface coverings.
    3. Frost fillings.
    4. Vein fillings.
    5. Weathering products.
    6. Converging walls.
    7. Interrupted joints.
    8. Sea water.
  B. Lower confining agents.
    1. Impervious foot walls.
    2. Vein fillings (cementation).
    3. Converging walls.
    4. Interrupted joints.
    5. Fresh water.
    6. Sea water.
    7. Heat.
    8. Pressure.

BEDDED ROCKS.

UPPER CONFINING AGENTS.

Impervious bed.—The term "impervious bed" is here used to designate a bed of stratified material through which water penetrates with difficulty—the sense in which it has been used in practically all previous discussions of artesian waters. In general it has been assumed that such a bed—relatively impervious as compared to the water bed—is essential to artesian flows, and it has been so shown in practically all figures illustrating artesian systems. As a matter of fact, however, it need not be absolutely impervious. In the words of Chamberlin,[a] "a stratum that successfully restrains the most of the water, and thus aids in yielding a flow, is serviceably impervious." Clays furnish the best confining strata, being both impervious in character and free from open joints or other fractures that permit the water to pass through. Shales are generally accounted as second in value. Some limestones, as the Clinton of southwestern Ohio, are good confining agents, but most rocks of this kind are broken by joints that afford numerous points of leakage.

Stratification planes.—At several places in Michigan and elsewhere flows have been procured from homogeneous sands. As has been explained in another report,[b] the cause of the confinement may probably be found in the arrangement and shape of grains. All materials that afford flows of the nature described are stratified—in other words, they were deposited in layers, which, though composed of

[a] Chamberlin, T. C., The requisite and qualifying conditions of artesian wells: Fifth Ann. Rept. U. S. Geol. Survey, 1885, p. 138.

[b] Fuller, M. L., Two unusual types of artesian flow: Water-Sup. and Irr. Paper No. 145, U. S. Geol. Survey, 1905, pp. 41–45.

material of uniform grain, were nevertheless laid down successively one over another as independent horizontal laminæ. This process develops conditions that are more favorable to the transmission of water along the laminæ than across them, due in part simply to the lamellar arrangement.[a] There is, however, another factor present—namely, the irregularity of the shape of grains—which has probably considerable influence in regulating the flow of water through the sand. In sediments, such as gravel and sand, the particles no matter how uniform their size are not symmetrical in shape. One axis is almost sure to be longer than the other (fig. 2), and when deposition takes place the grains have a strong tendency to arrange themselves with their longer axes horizontal and to overlap one another to a greater or less extent, like the shingles on a house, though, of course, far less perfectly (fig. 3). Under such conditions it is clear that,

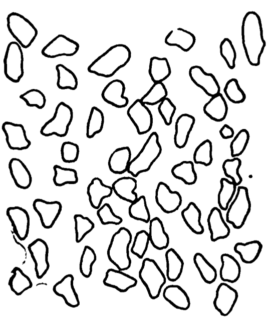


Fig. 2.—Form of sand grains.

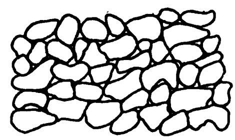


Fig. 3.—Arrangement of sand grains in stratified deposits.

although the material is pervious and may hold large amounts of water, the passage of water across the planes of stratification will be difficult, at least as compared with its passage along those planes. A well that enters such material will afford an upward path for the water that is easy as compared with its passage through stratified material of the character described, and a flow will often result.

Friction.—Friction alone seems to be competent under certain conditions to produce the necessary confinement, especially where the reservoir is fed at the bottom. If, for instance, water should enter at the bottom of a thick bed of fine, uniform, and structureless sand under a head sufficient to lift it 100 feet through the sand it would rise in a pipe tapping it at the bottom to a height greater than its level in the sand outside, the difference being determined by the relative amounts of friction in sand and pipe. This factor may be as common in producing flows as the factor of stratification described above.

[a] This overlapping of grains has been described by W. O. Crosby in his discussions of "hard-packed" sand in glacial deposits at Clinton, Mass. (Tech. Quart., vol. 17, 1904, pp. 61–62 and 67–70.) Although such sand is so deposited or "packed" that it strongly resists the advance of the drill, it nevertheless absorbs large quantities of water.

Mineral crusts.—When the water table is in porous materials and is fairly constant in level, mineral matter is frequently deposited along the upper surface, forming a sort of crust. A number of such crusts have been noted in the drift deposits of Michigan, Minnesota, and other States, while they are very common indeed in many of the desert regions. In Minnesota the crusts are of both iron and lime, and some of them are several inches thick. The iron crusts have the appearance of bog ore, resembling the similar deposits in Michigan.[a] As long as the water table remains stationary the crust has no effect, but whenever a rise takes place, due to rainfall entering at higher points, the crust holds back the water with the result that a material artesian pressure is quickly developed. (See fig. 9, p. 41.)

In the desert regions the crusts, known as "caliche," are composed mainly of calcium carbonate and occur at various levels, ranging from 3 or 4 feet below the surface to considerable depths. These crusts appear to be of different origin at different localities, being due in part to the evaporation of waters brought up by capillarity, as postulated by Blake;[b] in part to precipitation from underground waters, by reason of the loss of carbon dioxide on the release of pressure, as suggested by Lee;[c] and in part to downward leaching and concentration of rain waters, as urged by R. H. Forbes.[d] Like the crusts previously mentioned, they may serve as confining beds whenever there is any rise of the water table due to rainfall at higher points.

Frost zones.—The action of frost zones, such as frozen soils, is very similar to that of the crusts just described. Such frozen crusts form at the bases of gentle slopes along valleys, or wherever the water table comes to the surface, and extend back under the high ground to points where the water is no longer within reach of frost. Where the slope is gentle this may be some distance. The soil farther back not being saturated is often not frozen at all, especially in sandy and other well-drained materials. Under such conditions rain water not uncommonly sinks downward in the unfrozen region and raises the water table, with the result that the pressure is transmitted beneath the frozen soil. If the frozen crust is penetrated at such times the water will flow at the surface. (See fig. 9, p. 41.)

Confined air and gas.—While waters rising under the influence of gas pressure are not regarded as artesian, air and gas can not be excluded from the list of confining agents. Water is just as effectually

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[a] Leverett, Frank. Flowing wells and municipal water supplies in the southern portion of the Southern Peninsula of Michigan: Water-Sup. and Irr. Paper No. 182, U. S. Geol. Survey, 1906, pp. 8–9.

[b] Blake, W. P., Caliche of southern Arizona: Trans. Am. Inst. Min. Eng., vol. 31, 1901, p. 220.

[c] Lee, W. T., Underground waters of Salt River valley, Arizona: Water-Sup. and Irr. Paper No. 136, U. S. Geol. Survey, 1905, pp. 107–111.

[d] Quoted by Lee, ibid., p. 110.

prevented from reaching the crest of a gas-bearing anticline by the gas pressure as if an impervious bed intervened, and one is as truly a confining agent as the other. Confined air may likewise limit the rise of water in dome-like caverns in limestone, while confined air in earth, when prevented from upward escape by frozen or saturated soil zones, often acts temporarily as a confining stratum.

Fresh water.—The action of fresh water as a confining agent can not be better described than in the words of Chamberlin:[a]

> Paradoxical as it may seem, water itself may form a confining agent. * * * If the water between the well and fountain head is actually higher than the latter, it will tend to penetrate the water-bearing stratum, so far as the overlying beds permit, and will, to that extent, increase the supply of water seeking passage through the porous bed, and will, by reaction, tend to elevate the fountain head, if the situation permit. I conceive that one of the most favorable conditions for securing a fountain is found when thick semiporous beds, constantly saturated with water to a greater height than the fountain head, lie upon the porous stratum, and occupy the whole country between the well and its source. This is not only a good, but an advantageous, substitute for a strictly impervious confining bed. Under these hydrostatic conditions, limestone strata reposing on sandstone furnish an excellent combination.

It should be noted, however, that although an impervious cover is not postulated the water bed is assumed to be relatively more porous than the confining stratum, and no recognition is made of flows from uniform materials, as described on pages 21, 22. The latter, however, adds even more emphasis to the importance of water as a confining agent than did the conditions described by Chamberlin.

Sea water.—When porous deposits extend outward beneath the sea, as along sandy coasts, the fresh waters moving from the land rise from below against the pressure of the sea water. As sea water has a specific gravity of approximately 1.027 it will hold up a column of fresh water of materially greater length, and when the head of the fresh water is less, as is frequently the case, than the excess of weight of the sea waters, the latter may act as effective confining agents. (See p. 43.)

LOWER CONFINING AGENTS.

What has been said of the upper confining agents applies in many instances with equal force to the lower confining agents. The under bed, like the upper, may be any "bed that successfully retains most of the water," whether absolutely impervious or not. Stratification planes may limit the downward penetration of the water in thick beds as it does the upward movement, and friction may produce the same result, especially in slightly inclined beds of great extent. Mineral crusts are more common as an upper restraining agent than

[a] The requisite and qualifying conditions of artesian wells: Fifth Ann. Rept. U. S. Geol. Survey, 1885, pp. 138, 140.

as a lower, but cases undoubtedly occur where the water is confined between two such layers. Water is found between frozen layers of soil in Alaska. Confined air often acts temporarily as an under confining agent, as in the saturated zones upheld by the air of soils during heavy downfalls of rain, and confined gas may possibly act similarly. Previously absorbed fresh waters, by saturating the deeper rocks, limit the depth of circulation of waters entering subsequently. Sea water is even more important as an underlying stratum than as an upper confining layer. In addition to the preceding agents, which act both as upper and lower confining agents, general cementation, heat, and pressure are effective factors in limiting the downward penetration of water under certain conditions.

Cementation.—Cementation is the process by which the grains of sedimentary rocks are bound together and the intervening pores filled by the deposition of mineral matter from infiltrating solutions. Unlike the formation of crusts, this deposition does not result from evaporation, but from the supersaturation of solutions at depths far below the water table. It is not usually limited to a single layer, or point, but is a general process affecting large bodies of rock over wide areas. The conversion of open porous sandstones to dense impervious quartzites by the deposition of silica is perhaps the best example of the process, which is notably efficient in limiting the downward penetration of waters.

Heat.—It has often been assumed that the circulation of water, owing to its supposed conversion into steam, is limited to relatively moderate depths, but it can be readily shown that the rise of the boiling point due to increased pressure ordinarily more than counterbalances the increased heat at great depths, and that under any of the usually accepted rates of increment, change to steam will not take place. When water approaches uncooled igneous intrusions that lie at shallow depths, however, conversion to steam may occur, and the downward penetration of the water may be stopped. This is probably a common factor of limitation in igneous regions and may possibly act in regions where the temperature gradient is particularly high.

Pressure.—Pressure, as shown by Hoskins,[a] closes all ordinary cavities at about 10,000 meters and imposes an effectual limit to the penetration of free water, although rock-inclosed, liquid-filled cavities can exist to a depth at which water and rocks are miscible in all proportions. As a matter of fact, pressure is probably rarely an important factor in limiting the penetration of water in the unaltered bedded rocks because of their essentially superficial occurrence.

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[a] Hoskins, L. M., Flow and fracture of rocks as related to structure: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845–875.

JOINTED ROCKS.

UPPER CONFINING AGENTS.

Impervious wall.—In the same way that an impervious overlying bed is a leading restraining agent in bedded rocks the impervious hanging wall of an inclined joint is a prominent confining agent in jointed rocks. Like the former, it may not be absolutely but only relatively impervious, but owing to the fact that joints are mainly developed in dense or massive rocks, especially in the fine-grained types, the joint wall is on the average considerably more impervious than the cap rock in bedded formations.

Impervious covering on surface.—This is a very common restraining agent in jointed or fissured rocks. It is especially well shown in the extensive "lake-bed" region of southeastern Michigan, where artesian water, under pressure enough to lift it to the surface, is confined over considerable areas in jointed and fissured limestone, etc., by the overlying clayey till and "lake-bed" deposits.[a] The numerous flows from granite beneath alluvium in valleys in the Piedmont area of the Southern States is due to the same causes. (See figs. 11 and 14, pp. 41, 42.)

Frost fillings.—In winter water freezes almost as fast as it seeps out at the surface, and it is not uncommon to find that joint openings through which water is ordinarily rising are frozen solid to some distance from the surface. The ice under such conditions may present an effective barrier to the water pressing upward from below.

Vein fillings.—Water coming up from below and carrying an excess of mineral matter in solution not infrequently deposits it in the openings near the surface, sometimes closing the joint openings as completely as they are closed by ice. Mr. G. O. Smith has described such fillings and considers them the probable confining agents that give rise to the artesian flows from the crystalline rocks in parts of New Hampshire and Maine.[b]

Weathering products.—The usual action of the weather is to widen the joints and other partings, but occasionally, where the circulation is slight, the clayey products of decomposition are not entirely removed, but collect in the joints and other available openings, sometimes clogging them sufficiently to render them effective obstacles in the path of uprising waters. The closing of joint passages due to the expansion resulting from the process of hydration in rocks undergoing weathering is also a possible factor in restraining underground water circulation.

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[a] Fuller, M. L., Two unusual types of artesian flow: Water-Sup. and Irr. Paper No. 145, U. S. Geol. Survey, 1905, pp. 40–45.

[b] Water resources of the Portsmouth-York region, New Hampshire and Maine: Water-Sup. and Irr. Paper No. 145, U. S. Geol. Survey, 1905, pp. 120–128.

Sea water.—Because of its greater density, sea water exerts in jointed rocks, as in bedded rocks, a decided restraining influence on uprising fresh waters, even when their head is somewhat higher than sea level, and it is a possible factor in affording the confinement necessary for some of the flows from jointed rocks when near sea level.

Converging walls.—The converging of the joint walls near the top may be due to mineral deposition on the sides, to expansion of the wall rock due to weathering, to local pressure developed through faulting or readjustments of the joint blocks, or to the relative absence of solution as compared to that at greater depths. A contraction of the opening sufficient to exert a decided restraining influence on the underground waters may result from any of the causes indicated.

Interruptions of joints.—Joints are not of unlimited extent, although some of the master joints may be miles in length. A joint may terminate either by gradual contraction and disappearance or by ending abruptly against an intersecting joint or other plane. This is especially true of intersecting horizontal and vertical joints, the latter frequently ending abruptly against the former. As most horizontal joints are less open than vertical joints, the termination is at many places such as to prevent circulation beyond it.

LOWER CONFINING AGENTS.

The lower confining agents are not greatly different from the similar agents in bedded rocks or from the upper confining agents in jointed and fractured rocks already described. The impervious foot wall is comparable with the impervious hanging wall and is subject to the same qualifying statements. Frost filling and weathering play little or no part in fixing the lower limit of penetration, but vein fillings are as likely to occur at considerable depths as at the surface, and are probably not infrequently a factor of importance. The convergence of walls and the interruption or termination of joints are doubtless of even greater importance than as upper confining agents. Fresh and sea waters limit the downward penetration as in the bedded rocks, and, similarly, heat and pressure may locally play important parts.

NATURE OF ARTESIAN CIRCULATION.

Artesian circulation takes place by virtue of the variations in the pressure to which the water is subjected in different parts of its reservoir. By definition of the artesian principle (p. 7) all factors except hydrostatic pressure are excluded as determining causes of circulation. There are, nevertheless, a number of modifying agencies which in some cases exert a powerful influence on the water head or movement. The more important of the controlling and modifying factors may be summarized as follows:

Factors in artesian circulation.

I. Primary factor.
  A. Gravity.
II. Modifying factors.
  A. Factors mainly affecting pressure.
    1. Barometric variations.
    2. Temperature variations.
    3. Density of waters.
      a. Variations due to temperature.
      b. Variations due to dissolved salts.
      c. Variations due to suspended solids.
    4. Height of adjacent water levels.
      a. Water table.
      b. Neighboring water bodies.
      c. Levels dependent on floods.
      d. Levels dependent on tides.
      e. Levels dependent on winds.
    5. Rock pressure.
  B. Factors mainly affecting movement.
    1. Porosity.
    2. Size of grain or openings.
    3. Temperature.

PRIMARY FACTOR.

Gravity.—The leading factor in artesian circulation is gravity, from which fact it follows that (disregarding friction) the pressures in the opposing arms of an artesian system will be proportional to the heights of the respective water columns, while the effective head will be determined by the difference in the two. The hydrostatic pressure dependent on gravity is the sole recognized cause of artesian pressure as the term is here used (p. 7), although its action is modified in many ways by the qualifying factors considered below.

The operation of the ordinary hydrostatic law is limited to appreciable openings. According to Daniel[a] such openings, which are known as supercapillary and include joints, faults, bedding planes, some fissility planes, the pores of sandstones, etc., have for their minimum limit a diameter of 0.508 mm. in tubular passages and a width of 0.254 mm. in sheet openings of the joint or bedding-plane types.

MODIFYING FACTORS.

The factors which modify the pressures resulting from gravity may be divided into those which cooperate directly with the latter in determining the hydrostatic pressure, and those which primarily affect the movement of the water and only incidentally influence the pressure.[b]

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[a] Daniel, Alfred, Text Book of Physics, 3d ed., 1894, pp. 277, 316.

[b] For an extended discussion of the factors giving rise to fluctuations of water level, see Veatch, A. C., Fluctuations of the water level in wells: Water-Sup. and Irr. Paper No. 155, U. S. Geol. Survey, 1906.

FACTORS MAINLY AFFECTING PRESSURE.

BAROMETRIC VARIATIONS.

For each locality there is a normal barometric pressure dependent upon elevation, latitude, and distance from the ocean. This, however, is subject to many influences, both cyclic and irregular, which materially modify the ultimate pressure. The barometric factors may be classified as follows:

Barometric factors.

I. Constant factors.
  1. Elevation.
  2. Latitude.
  3. Distance from ocean.

II. Variable factors.
  1. Cyclic.
    a. Diurnal variations.
    b. Seasonal variations.
    c. Variations due to solar movements.
    d. Variations due to lunar movements.
  2. Irregular.
    a. Atmospheric disturbances.
    b. Cyclones.
    c. Storms.
    d. Cloudiness.
  3. Topographic surroundings (independent of altitude).

Although many of the factors are very weak in their action all are measurable, and, with the exception of solar and lunar movements, cloudiness, and topography, all are known to exert an appreciable influence on wells. In some instances the resultant effects appear to be far greater than those that would be due to the actual differences in pressure at the point of observation. The cause of this is as yet unknown, but it is possible that it may prove to be related to those producing the remarkable seiches of the Great Lakes, some of which are marked by a change of water level as great as 6 feet. It is not improbable that under favorable conditions all the variations noted have a material effect on underground waters. The manifestations are most noticeable at periods of low barometer and include increase of head, increase of flow, muddiness, and discoloration.

TEMPERATURE VARIATIONS.

Temperature acts on artesian circulation through its influence on the viscosity of the water, through the expansion and contraction of included air or gas, by variations in the pressure of confined air or gas upon water surfaces, and by its influence on the density of the artesian waters. Of these viscosity mainly affects the water move-

ment directly, although it incidentally affects the head through its influence on friction. The expansion and contraction of included gases has a direct affect on pressure and head. The influence of temperature on density is considered below.

DENSITY OF WATERS.

Variations due to temperature.—Water expands about 4.3 per cent when heated from its point of greatest density (39.2°) to the boiling point and gives rise, in the case of long columns, to notable variations of volume and density. The difference in weight of cold and warm columns, and the resultant increase in the length of the latter, has been cited as an important factor in deep circulation, especially at the Sea Mills of Cephalonia.[a] The considerable streams which leave the ocean at this point and disappear into limestone crevices at sea level can only regain the surface at equal or higher levels. This result can apparently be attained only through the action of temperature or some other force that affects the density.

Variations due to dissolved salts.—Besides temperature, the weight of water depends largely upon composition, the weight increasing materially according to the amount of mineral matter in solution. Sea water has a specific gravity of 1.027 as compared with 1, the specific gravity of fresh water, from which it follows that a column of salt water 100 feet in height will support nearly 103 feet of fresh water. Even allowing for only relatively slight variations in density we have sufficient differences in pressure to produce circulation. This is thought to be a more effective cause than temperature in producing the circulation at the Sea Mills of Cephalonia mentioned above.[b]

Variations due to suspended solids.—The action is similar to that of dissolved mineral matter, but is usually much more pronounced. It is best illustrated by certain phenomena exhibited in the jet process of well drilling, in which clear water is forced under pressure down a small tube inside a larger one, the materials detached by the current being carried to the surface in the space between the inner pipe and the outside casing. When the pressure is removed from the small tube the water is often found to rise in it materially above the height of the well and to flow for some moments at elevations several feet above the surface, the water between the inner and outer tube sinking at the same time. This peculiar action seems to be due entirely to the high density of the mud- or sand-laden waters in the large tube as compared with the clear and lighter water in the inner pipe.

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[a] Crosby, F. W., and Crosby, W. O., Tech. Quarterly, vol. 9, 1896, pp. 6-23.

[b] Fuller, M. L., Conditions of circulation at the Sea Mills of Cephalonia: Bull. Geol. Soc. America, vol. 18, pp. 221-232.

HEIGHT OF ADJACENT WATER LEVELS.

Water table.—The height of the water table over any point in an artesian system may exert a material influence on the pressure. In fact, this may be a far more important factor than the pressure transmitted from the more remote catchment area. This action has been discussed in greater detail on page 24.

The level of the water table is controlled by a great number of factors, among which may be mentioned the amount of rainfall, the amount of evaporation, and the porosity of materials. The ground water does not usually respond at once to the rainfall, owing to the length of time that the water requires to penetrate the unsaturated upper materials; nor does the rise correspond in amount to the precipitation, because of losses by evaporation, absorption by vegetation, and the retention of a portion in the unsaturated zone. In very heavy rainfall a saturated zone may be formed at the surface, constituting a temporary perched water table, when the main water table may be affected almost immediately owing to the transmission of pressure by the air confined beneath the saturated layer.

Neighboring water bodies, etc.—The level of lakes and streams is commonly a function of the height of the ground water in the vicinity, but sometimes the reverse is true and the ground-water level becomes a function of the level of the water bodies on the surface. The latter may also in some cases influence to considerable extent the pressure on underlying confined waters.

The effects of surface water bodies on the underground waters may be summarized as follows:

Effects of height of surface water bodies on underground waters.

I. Changes of ground-water levels.
   1. Changes due to variation of level of surface streams receiving ground-water discharge.
   2. Changes due to movements away from surface water bodies.

II. Variations of pressure on confined waters.
   1. Changes due to communication between surface and underground water bodies through intervening beds.
      a. Communication through joints and other passages.
      b. Communication through the body of the intervening beds.
   2. Changes due to transmission of pressure through intervening beds.
   3. Changes due to plastic deformation.

The cause of the changes of ground-water levels resulting from variations in the height of the surface water bodies which receive the underground drainage is apparent. When such bodies are low the movement of ground waters is accelerated and the water table depressed, while when they are high the underflow is slackened and the water table elevated.

In pronounced rises of the water levels in surface bodies due to floods, tidal fluctuations, banking of waters under the action of strong winds, or to other causes arising from conditions developing outside of the immediate area affected, the ground water is no longer able to issue at its normal level. In fact the rising waters act primarily as a dam, raising the level of discharge of the ground waters and ponding them up like the backwater behind an artificial dam. When the rise is more rapid than in the inflowing ground water an actual outward movement from the surface body may take place, producing a corresponding rise of the ground water.

Another effect of the rise of surface waters is a downward penetration of such water (due to the increased pressure) through the underlying retaining beds into more porous water beds below. This takes place in part through joints and similar passages, which are present even in soft, unconsolidated clays, and in part, perhaps, through the body of the material itself. In either case a very slight movement is sufficient to produce a pronounced rise in the waters of wells. Considering an area 1,000 feet square, a downward water movement of only one one-thousandth of a millimeter through a clay or other capping would be equivalent to a rise of approximately 25 feet in a single well, or 1 foot in 25 wells.

The transmission of pressure through the so-called impervious beds is probably sometimes a factor of artesian head, even though no movement of water through the beds takes place. Some quicksands, although they will yield little or no supplies to a well, often carry from 30 to 50 per cent of water, some of which is in supercapillary openings and hence is capable of transmitting hydrostatic pressure even when motion is prevented by excessive friction (using the term in its broader sense to include the resistance of inertia as well as the resistance to motion).

Still another result, which may be more common than is usually suspected, is the increase of pressure on confined waters, due to the plastic deformation of impervious beds under the varying loads resulting from changes in the water level of overlying streams, lakes, or the sea. This is especially noticeable in wells along the sea coast, which commonly fluctuate with the tide, even though the water horizon lies deep below the surface and is separated from it by thick beds of impervious clays, etc. The figures applying to the downward water movement in the preceding paragraph are equally applicable to deformation and emphasize the slight amounts necessary to account for the observed fluctuations in wells.

ROCK PRESSURE.

In addition to the deformation of the nature described in the preceding paragraph, pressure may be exerted by virtue of the weight of the overlying materials alone. This is probably not a common factor, but extensive sinkings of the ground have followed the pumping of water from mines and the withdrawal of the support afforded by hydrostatic pressure, indicating that the rock pressure on the water must have been considerable, at least locally.

In the process of warping and folding the pressure of the rocks on the waters in their joints or other openings may often be important, especially when the disturbance is accompanied by faulting. Considerable quantities are excluded from such openings during earthquakes, and it is probable that the action underground is of much greater extent than the surface manifestations.

FACTORS MAINLY AFFECTING WATER MOVEMENTS.

The principal factors affecting underground water movements are porosity, size of grain or openings, and temperature. The first and second are factors of capacity, while all three are factors of friction. Their action is not wholly on movement, but through friction they have a decided, though indirect, influence on pressure. From the formula of velocity as computed by Allen Hazen [a] the following expression for loss of head is obtained: $h=\frac{vl}{cd^2\,(.70+.03t)}$.

In this formula h is the loss of head, v the velocity in meters daily, l the distance through which the water passes, c a constant factor, approximately 1,000, d the effective size of grain in millimeters, and t the temperature on the centigrade scale. For velocity the formula becomes:

$$v=cd^2\frac{h}{l}(.70+.03t)$$

From these formulæ it appears that high porosities, large grains, and high temperatures all accelerate water movement.[b]

REQUISITES OF ARTESIAN FLOWS.

Having outlined the more important conditions bearing on the occurrence and movements of underground waters, we are in a position to discuss the controlling factors of artesian flow. In doing this it is necessary to point out some of the objections to certain of the commonly postulated requisites.

[a] Some physical properties of sands and gravel: Rept. Massachusetts State Board of Health, 1892, p. 541.

[b] For a detailed description of the action see paper by C. S. Slichter on The motion of underground waters: Water-Sup. and Irr. Paper No. 67, U. S. Geol. Survey.

OBJECTIONS TO COMMON REQUISITES.

Since the appearance in 1885 of the paper of T. C. Chamberlin on the "Requisite and qualifying conditions of artesian wells"[a] a single set of requisites has, with one or two exceptions, been followed by writers of underground water papers. These, in brief, are as follows: (1) A pervious stratum to permit the entrance and the passage of water; (2) a water-tight bed below to prevent the escape of water downward; (3) a like impervious bed above to prevent the escape upward, for the water, being under pressure from the fountain head, would otherwise find relief in that direction; (4) an inclination of these beds, so that the edge at which the waters enter will be higher than the surface at the well; (5) a suitable exposure of the edge of the porous stratum, so that it may take in a sufficient supply of water; (6) an adequate rainfall to furnish this supply; and (7) an absence of any escape for the water at a level lower than the surface at the well.

There is one very serious objection to the requisites outlined above, namely, they apply only to a single class of flows—those from stratified rocks—and neglect not only flows from other varieties of rock, but even other types of flow from the same rocks. There are, moreover, many exceptions to the postulated requisites, which, taken in connection with the limitations mentioned, make new and more comprehensive definitions desirable. Some of the objections to the requisites are mentioned below.

Pervious stratum.—A pervious stratum, although a common form of reservoir, is seldom essential to artesian flows. In addition to the porous stratum postulated by the first requisite, flows may be obtained from lamination, bedding, cleavage, and shearing planes, from solution passages and mechanically eroded reservoirs, from vesicular zones in igneous rocks, from irregular joint and fault fractures, and from vein and igneous contacts. Metamorphic and igneous, as well as stratified rocks not only may, but actually do, yield flows at a large number of places; at many others the water falls only a few feet short of the surface; while in practically all wells the waters rise materially when encountered—that is, are truly artesian.

With the exception of the vesicular lavas the sources of water mentioned are not in the nature of beds, but are in the form of actual openings, a type of passage not recognized in the older requisites.

Impervious bed below.—In view of the nature of the reservoirs mentioned in the preceding paragraph and discussed in greater detail on pages 8–15 it is apparent that the second requisite—the impervious underlying stratum—loses much of its force. Such impervious

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[a] Fifth Ann. Rep. U. S. Geol. Survey, pp. 125–173.

beds are, it is true, adjuncts to many flows in stratified rocks, but numerous other agents may serve the same purpose. In bedded rocks the following may be mentioned: Stratification, friction, mineral crusts, frost zones, confined air and gas, fresh or salt water, cementation, heat and pressure. In jointed and fractured rocks impervious foot walls, vein fillings, converging walls, interrupted joints, fresh and salt water, heat and pressure are the most important. Discussions of the agents in bedded rocks will be found on pages 24–25 and of jointed and fractured rocks on page 27.

Impervious bed above.—The objections to the postulation of an upper impervious bed are similar to those of the lower confining bed just enumerated. In the bedded rocks the following, in addition to the postulated impervious stratum, may serve as confining agents: Stratification, friction, mineral crusts, frost zones, confined air and gas, fresh water, and sea water. In the jointed and fractured rocks the impervious hanging wall, impervious surface coverings, frost and vein fillings, weathering products, converging walls, interrupted joints, and sea water may be mentioned in addition. For a discussion of these agents see pages 21–24, 26–27.

Inclination of beds.—Inclination of the water-bearing bed, while a common factor of artesian flows, is by no means essential. At many places water appears to penetrate lenses of sandstone in rocks, like those of the Carboniferous of Pennsylvania, through joints and similar openings, and flows may be obtained independent of any inclination of the bed affording the water. The same is true of the horizontal beds yielding flows by virtue of the opposition of the stratification planes to upward movements, as described on page 22. Joint and solution passages also afford artesian flows independent of any inclination at the point penetrated.

In both bedded and crystalline rocks the pressure must of course be transmitted from connecting passages or other water reservoirs at higher levels, but the supply itself does not necessarily come from a higher level, since besides the downward moving meteoric waters, sea waters, waters chemically or physically excluded from the crust, and waters excluded directly from the centrosphere or indirectly through magmatic intrusions all furnish supplies. These sources are discussed on pages 17–20.

Outcrop of porous stratum.—The postulated suitable exposure of the edge of the porous stratum so that it may take in a sufficient supply of water, though a common, is likewise far from an essential factor of artesian flows. The horizontal sandy beds from which the flows are obtained in Long Island and Michigan, as described on page 22, nowhere outcrop, the water penetrating directly downward through the overlying layers. It is believed that in many other places the water and pressure are communicated to the deep-lying por-

ous beds through joints rather than from remote outcrops. Moreover, throughout extensive areas of the Silurian, Devonian, and Carboniferous rocks in Pennsylvania, West Virginia, and Ohio, in the areas underlain by Cretaceous beds near Fort Monroe, Va., in the region about Wilmington, N. C., and in many lesser areas elsewhere, the deep artesian waters appear to represent originally included sea waters and not waters entering at the outcrops. Other sources, including waters derived from the crust by chemical or physical exclusion or by direct or magmatic exclusion from the centrosphere, may furnish artesian supplies independent of the conditions of outcrop. (See pp. 17–20.)

Adequate rainfall.—Since the salt waters of the Carboniferous and Coastal Plain rocks just described, as well as magmatic waters, are actually derived over extensive areas from sources other than rainfall, it is clear that rainfall should not be regarded as an absolute requisite to artesian flow.

Points of escape.—There are very few artesian systems in which there is not more or less leakage. In the thicker and more persistent beds the leakage is often sufficient to insure circulation for long distances from the outcrop. Thus, in the Cretaceous beds beneath Charleston, S. C., and Savannah, Ga., fresh water has replaced salt water at least as far as the seacoast, or over a distance of more than 100 miles from their outcrop. At Fort Monroe, Va., and at Wilmington, N. C., on the other hand, there appears to be but little leakage, and the fresh water circulation is much less extensive, only salt water being obtained at the localities mentioned. The absence of leakage appears to have determined the presence of salt waters in the oil-bearing rocks of Pennsylvania and elsewhere.

In order that leakage may prevent flows, it must take place near the point at which the water horizon is tapped. Chamberlin and others have shown that its influence is limited, and the requisites should therefore postulate the absence of near-by leakage rather than the entire nonoccurrence of leakage.

ESSENTIALS OF ARTESIAN FLOWS.

The essentials of artesian flows, as recognized by the writer, are as follows:

1. An adequate source of water supply.
2. A retaining agent offering more resistance to the passage of water than the well or other opening.
3. An adequate source of pressure.

The first requisite is not made specific as regards source, because, as has been pointed out, artesian waters are not derived from a single but from a variety of sources. The second requisite—the retaining

agent—may be a stratum, a vein or dike wall, a joint, fault, or other fracture plane, a water layer, or some one of a variety of other agents. (See pp. 20–27.) The pressure, although primarily due to variations in level in the different parts of the artesian system, may be transmitted in so many ways and is subject to so many modifying factors that the postulation of a specific cause is impracticable.

MODIFYING FACTORS.

It is believed that the three factors stated in the preceding paragraph are all that can be considered as essential to artesian flows, all other postulated requisites being in reality modifying or accessory rather than essential factors. These secondary factors may be classified as follows:

Secondary factors of artesian flows.

I. Hydrostatic factors (relating to pressure and movement).
    1. Factors mainly affecting pressure.
        a. Barometric pressure.
        b. Temperature.
        c. Density.
        d. Rock pressure.
    2. Factors mainly affecting movement.
        a. Porosity.
        b. Size of pores or openings.
        c. Temperature.
II. Geologic factors (relating to reservoir).
    1. Character of reservoir.
    2. Retaining agents.
    3. Structure of reservoir.
    4. Topographic conditions.
    5. Conditions relating to supply.
        a. Catchment conditions.
        b. Condition of underground feed.
    6. Conditions of leakage.

The action of the various factors has already been indicated in connection with the foregoing discussion and no further statements are necessary.

TYPICAL ARTESIAN SYSTEMS.

In closing attention may be called to a number of the more common types of artesian systems. The artesian basin is the one most commonly figured, but in reality it is far less common than the artesian slope. Artesian flows from uniform horizontal beds appear to be common in many places, especially in the drift deposits of Michigan, but the areas of such flows in a single locality are limited. Flows from bedding planes appear to be not infrequent in the denser rocks, in which the beds themselves are not porous, but they depend on local conditions, and the flows can seldom be predicted. Flows

from solution passages appear to be fairly common, notwithstanding the local character of the passages. The necessary confinement doubtless results from constrictions of the openings due to local zones of relatively insoluble rock, to clogging by débris entering through sinks, to the caving of the walls, to the accumulations of silt in the more sluggish passages, etc. Flows from lamination planes appear to occur in certain shales and slates, while joints furnish one of the most widely prevalent types of artesian systems in the country. In fact practically all crystalline rocks, both igneous and metamorphic, as well as the jointed types of sedimentary rocks, contain water under strong artesian pressure; and while flows are not abundant they are found at short intervals throughout the Piedmont Plateau of the eastern United States and will doubtless eventually be discovered at many other points where such rocks occur at the surface.

The following diagrams will serve better than descriptions to indicate the nature of some of the more common artesian systems.

ARTESIAN BASIN.

The section shown in fig. 4 presents a set of conditions that occur in typical form in the Dakota sandstone basin.

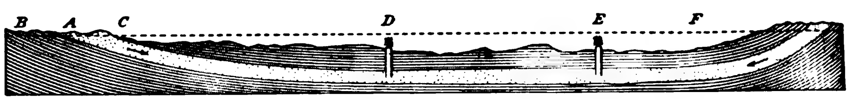

FIG. 4.—Section of an artesian basin. *A*, Porous stratum; *B*, *C*, impervious beds below and above *A*, acting as confining strata; *F*, height of water level in porous beds *A*, or, in other words, height in reservoir or fountain head; *D*, *E*, flowing wells springing from the porous water-filled bed *A*.

ARTESIAN SLOPE.

Fig. 5 shows a section of an artesian slope such as may be found in the Atlantic Coastal Plain. The dike shown in the figure, however,

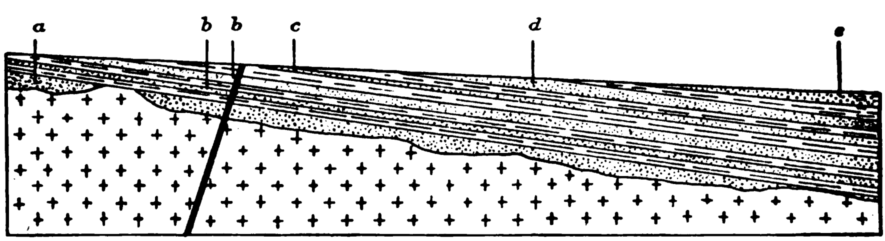

FIG. 5.—Section of an artesian slope. *a*, Water bed cut off by unconformity; *b*, beds cut off by dike; *c*, bed in which friction is the only obstruction to downward motion; *d*, porous bed changing to impervious; *e*, bed pinching out farther to the right.

does not usually occur in this area, although probable instances of such penetration occur in Georgia.

UNCONFINED HORIZONTAL BEDS.

The deep valleys occupied by the harbors of northern Long Island and some of the deep valleys in drift in northern Michigan present artesian conditions similar to those illustrated in fig. 6.

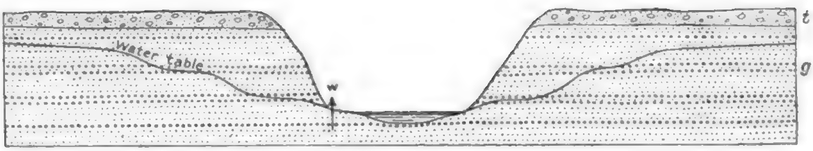

FIG. 6.—Section illustrating conditions governing flows from unconfined horizontal sands. *t*, Till; *g*, coarse sand and gravel; *w*, well.

BEDDING PLANES.

Conditions of artesian flow from horizontal bedding planes, fed by joints, are illustrated in fig. 7. A possible example of such conditions is afforded by the waters of the Trenton limestone in southwestern Ohio.

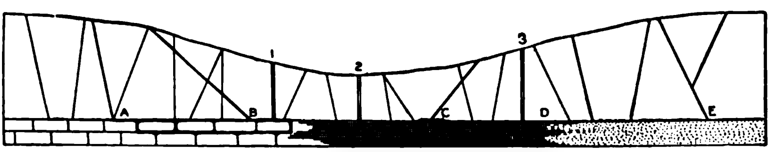

FIG. 7.—Section illustrating conditions of flow from horizontal bedding planes, etc., fed by joints. *A*, Water-bearing joints (indicated by the heavier lines); *B*, bedding planes between limestone and compact jointed rocks fed by joints at *A* and *B*; *C*, bedding plane between shale and compact jointed rocks with local circulation only; *D*, bedding plane fed from sandstone bed; *E*, sandstone bed fed by joints. 1, Flowing well from bedding plane between limestone and compact jointed rocks; 2, dry hole (no circulation along bedding plane); 3, flowing well from bedding plane fed from sandstone.

SOLUTION PASSAGES.

Some of the artesian flows of the Vicksburg limestone of the Atlantic Coastal Plain and of the Mississippian limestone of Kentucky may be cited as possible examples of flows from solution passages in limestone, illustrated in fig. 8.

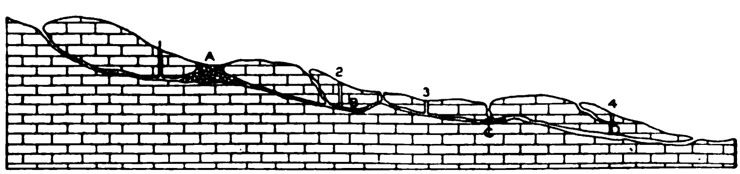

FIG. 8.—Section illustrating conditions of flow from solution passages in limestone. *A*, Brecciated zone (due to caving of roof), serving as confining agent to waters reached by well 1; *B*, silt deposit filling passage and acting as confining agent to waters reached by well 2; *C*, surface débris clogging channel and confining waters reached by well 3; *D*, pinching out of solution crevice resulting in confinement of waters reached by well 4.

FROST OR MINERAL CRUSTS.

The conditions of flow from beneath a frozen zone or mineral crust are represented in fig. 9. An example is seen in some of the open wells that overflow in spring.

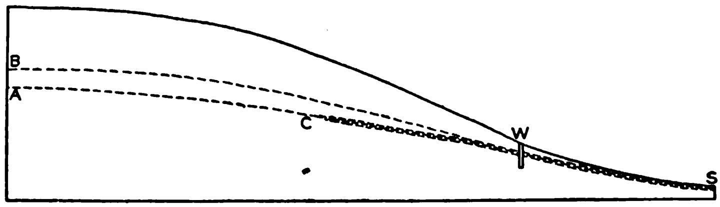

FIG. 9.—Section illustrating conditions of flow from beneath frozen zone or mineral crust. *CS*, Frost zone or mineral crust formed at surface of water table when at position *ACS*; *B*, position of water table under increased rainfall; *W*, flowing well resulting from confinement of water due to rise of head from *A* to *B*.

VESICULAR TRAP.

Fig. 10 illustrates conditions of flow from vesicular trap. Some of the wells penetrating the traps of the Newark group may be possible examples.

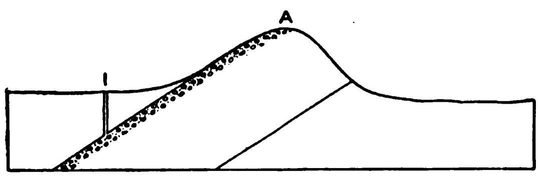

FIG. 10.—Section illustrating conditions of flow from vesicular trap. *A*, Vesicular zone feeding well 1.

WEATHERED ROCKS BENEATH CLAYS.

The "lake bed" area of southeastern Michigan furnishes an instance of the conditions of flow shown in fig. 11.

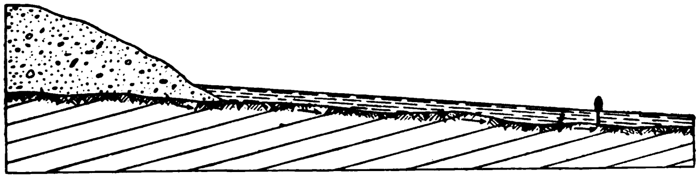

FIG. 11.—Section illustrating conditions of flow from joints, cracks, and solution passages in stratified rocks covered by impervious clays and fed from morainal drift.

JOINTED CRYSTALLINE ROCKS.

Artesian conditions in jointed crystalline rocks without surface covering are represented by the flowing wells in the granites of Maine and New Hampshire and are illustrated in fig. 12.

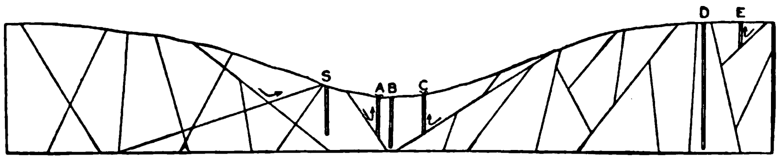

FIG. 12.—Section illustrating artesian conditions in jointed crystalline rocks without surface covering. *A, C,* Flowing wells fed by joints; *B,* intermediate well between *A* and *C* of greater depth, but with no water; *D,* deep well not encountering joints; *E,* pump well adjacent to *D,* obtaining water at shallow depths; *S,* dry hole adjacent to a spring, showing why wells near springs may fail to obtain water.

BASINS FED BY JOINTS.

Many of the basins between mountain ranges throughout the arid West illustrate the conditions of flow shown by fig. 13.

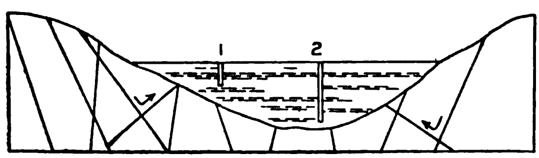

FIG. 13.—Section illustrating conditions of flow in alluvium-filled basins fed by joints. 1 and 2, Flowing wells from gravels beneath silts, fed from joints that carry water from surrounding mountains.

JOINT WATERS CONFINED BY ALLUVIUM.

The confinement of water in joints by valley silts, illustrated in fig. 14, occurs in many of the valleys of the Atlantic Piedmont Plateau.

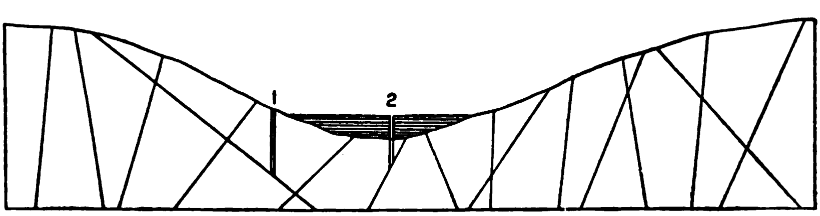

FIG. 14.—Section illustrating confinement of water in joints by valley silts. 1, Flowing hillside well resulting from obstruction of lower outlet by valley silts; 2, valley well failing to secure supplies because of action of silts in preventing entrance of water into the joints.

JOINT WATERS CONFINED BY SEA WATER.

Fig. 15 presents a section illustrating the action of salt water as a confining agent. Some of the low flowing wells near the coast of Maine and New Hampshire may be cited as possible examples.

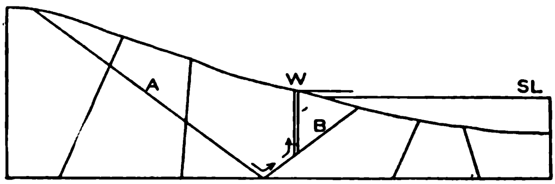

FIG. 15.—Section illustrating action of salt water as a confining agent, etc. *SL*, Sea level; *A*, open joint bringing down fresh water; *B*, open joint communicating pressure from heavier salt water; *W*, well slightly above sea level, obtaining flow in consequence of slight rise in head resulting from slightly greater pressure of water in joint *B* as compared to the water column in the well, due to the higher specific gravity of the salt water.

FOLIATION PLANES.

The section shown in fig. 16 illustrates the conditions of flow from foliation and schistosity planes, examples being found in the flows from upturned schistose slates in Maine.

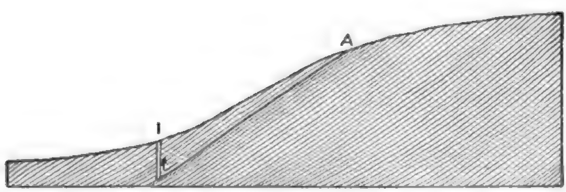

FIG. 16.—Section illustrating conditions of flow from foliation and schistosity planes. *A*, Foliation plane feeding flowing well 1.

FAULT AND CONTACT PLANES.

Possible conditions of flows from fault and contact planes are shown in ideal section in fig. 17. Poland Springs, Maine, presents an example of such conditions.

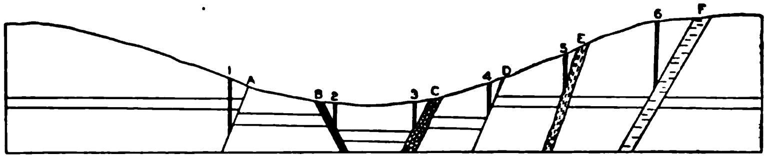

FIG. 17.—Ideal section illustrating possible conditions of flow from fault and contact planes. *A*, Reverse fault affording pump water to well 1, but no flow; *B*, sheet zone due to normal faulting feeding flowing well 2; *C*, crushed zone due to normal faulting yielding water to well 3; *D*, simple normal fault feeding well 4; *E*, vein affording water from contact to well 5; *F*, dike affording water from contact to well 6. *C*, *E*, or *F*, may also be conceived to represent sandstone dikes which may under certain conditions become important artesian reservoirs.

INDEX.

CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 319.]

The publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of the United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists can be had on application.

Most of the above publications can be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they can be obtained, free of charge (except classes 2, 7, and 8), on application.
2. A certain number are delivered to Senators and Representatives in Congress for distribution.
3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they can be had at prices slightly above cost.
4. Copies of all Government publications are furnished to the principal public libraries in the large cities throughout the United States, where they can be consulted by those interested.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports; Q, Fuels; R, Structural materials. This paper is the one hundred and twenty-second in Series B and the seventy-fourth in Series O, the complete lists of which follow (PP=Professional Paper; B=Bulletin; WS=Water-Supply Paper):

SERIES B, DESCRIPTIVE GEOLOGY.

B 23. Observations on the junction between the Eastern sandstone and the Keweenaw series on Keweenaw Point, Lake Superior, by R. D. Irving and T. C. Chamberlin. 1885. 124 pp., 17 pls. (Out of stock.)

B 33. Notes on the geology of northern California, by J. S. Diller. 1886. 23 pp. (Out of stock.)

B 39. The upper beaches and deltas of Glacial Lake Agassiz, by Warren Upham. 1887. 84 pp., 1 pl. (Out of stock.)

B 40. Changes in river courses in Washington Territory due to glaciation, by Bailey Willis. 1887. 10 pp., 4 pls. (Out of stock.)

B 45. The present condition of knowledge of the geology of Texas, by R. T. Hill. 1887. 94 pp. (Out of stock.)

B 53. The geology of Nantucket, by N. S. Shaler. 1889. 55 pp., 10 pls. (Out of stock.)

B 57. A geological reconnaissance in southwestern Kansas, by Robert Hay. 1890. 49 pp., 2 pls.

B 58. The glacial boundary in western Pennsylvania, Ohio, Kentucky, Indiana, and Illinois, by G. F. Wright, with introduction by T. C. Chamberlin. 1890. 112 pp., 8 pls. (Out of stock.)

B67. The relations of the traps of the Newark system in the New Jersey region, by N. H. Darton. 1890. 82 pp. (Out of stock.)

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B 108. A geological reconnaissance in central Washington, by I. C. Russell. 1893. 108 pp., 12 pls. (Out of stock.)

B 119. A geological reconnaisance in northwest Wyoming, by G. H. Eldridge. 1894. 72 pp., 4 pls.

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B 144. The moraines of the Missouri Coteau and their attendant deposits, by J. E. Todd. 1896. 71 pp., 21 pls.

B 158. The moraines of southeastern South Dakota and their attendant deposits, by J. E. Todd. 1899. 171 pp., 27 pls.

B 159. The geology of eastern Berkshire County, Massachusetts, by B. K. Emerson. 1899. 139 pp., 9 pls.

B 165. Contributions to the geology of Maine, by H. S. Williams and H. E. Gregory. 1900. 212 pp., 14 pls.

WS 70. Geology and water resources of the Patrick and Goshen Hole quadrangles in eastern Wyoming and western Nebraska, by G. I. Adams. 1902. 50 pp., 11 pls.

B 199. Geology and water resources of the Snake River Plains of Idaho, by I. C. Russell. 1902. 192 pp., 25 pls.

PP 1. Preliminary report on the Ketchikan mining district, Alaska, with an introductory sketch of the geology of southeastern Alaska, by A. H. Brooks. 1902. 120 pp., 2 pls.

PP 2. Reconnaissance of the northwestern portion of Seward Peninsula, Alaska, by A. J. Collier. 1902. 70 pp., 11 pls.

PP 3. Geology and petrography of Crater Lake National Park, by J. S. Diller and H. B. Patton. 1902. 167 pp., 19 pls.

PP 10. Reconnaissance from Fort Hamlin to Kotzebue Sound, Alaska, by way of Dall, Kanuti, Allen, and Kowak rivers, by W. C. Mendenhall. 1902. 68 pp., 10 pls.

PP 11. Clays of the United States east of the Mississippi River, by Heinrich Ries. 1903. 298 pp., 9 pls. (Out of stock.)

PP 12. Geology of the Globe copper district, Arizona, by F. L. Ransome. 1903. 168 pp., 27 pls.

PP 13. Drainage modifications in southeastern Ohio and adjacent parts of West Virginia and Kentucky, by W. G. Tight. 1903. 111 pp., 17 pls. (Out of stock.)

B 208. Descriptive geology of Nevada south of the fortieth parallel and adjacent portions of California, by J. E. Spurr. 1903. 229 pp., 8 pls. (Out of stock.)

B 209. Geology of Ascutney Mountain, Vermont, by R. A. Daly. 1903. 122 pp., 7 pls.

WS 78. Preliminary report on artesian basins in southwestern Idaho and southeastern Oregon, by I. C. Russell. 1903. 51 pp., 2 pls.

PP 15. Mineral resources of the Mount Wrangell district, Alaska, by W. C. Mendenhall and F. C. Schrader. 1903. 71 pp., 10 pls.

PP 17. Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian, by N. H. Darton. 1903. 69 pp., 43 pls.

B 217. Notes on the geology of southwestern Idaho and southeastern Oregon, by I. C. Russell. 1903. 83 pp., 18 pls.

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PP 21. The geology and ore deposits of the Bisbee quadrangle, Arizona, by F. L. Ransome. 1904. 168 pp., 29 pls.

WS 90. Geology and water resources of part of the lower James River Valley, South Dakota, by J. E. Todd and C. M. Hall. 1904. 47 pp., 23 pls.

PP 25. The copper deposits of the Encampment district, Wyoming, by A. C. Spencer. 1904. 107 pp., 2 pls. (Out of stock.)

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PP 27. A geological reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho, by Waldemar Lindgren. 1904. 122 pp., 15 pls.

PP 31. Preliminary report on the geology of the Arbuckle and Wichita mountains in Indian Territory and Oklahoma, by J. A. Taff, with an appendix on reported ore deposits in the Wichita Mountains, by H. F. Bain. 1904. 97 pp., 8 pls.

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Correspondence should be addressed to

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DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

THE DOWNTOWN DISTRICT OF LEADVILLE, COLORADO

BY

SAMUEL FRANKLIN EMMONS

AND

JOHN DUER IRVING

WASHINGTON
GOVERNMENT PRINTING OFFICE
1907

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ILLUSTRATIONS.

THE DOWNTOWN DISTRICT OF LEADVILLE. COLO.

By S. F. EMMONS and J. D. IRVING.

INTRODUCTION.

The present sketch and the accompanying map and sections are presented in advance of publication of the revised maps of the entire Leadville district because the underground data on which they are based have been in great measure determined by the actual observation of one or both of the two authors and are therefore more readily compiled than the data concerning the other parts of the areas mapped, where there are considerable portions with regard to which the information is either less certain or altogether wanting. This preliminary publication is also made for the further reason that the information herein contained is likely to be more immediately useful to those engaged in mining at Leadville, since, on account of the deep covering of gravel beds, it is difficult for them to form a sufficiently clear idea of the structural conditions of the rock mass beneath to enable them to explore to advantage for new ore bodies. It is hoped, moreover, that the criticisms that may be made by those actually engaged in mining in this area, who will necessarily be in possession of much later data than were accessible to the authors when they prepared the accompanying map, will be available in time to correct any obvious errors before its final publication in connection with the general map of the whole district. In preparing such a map it is found that in many parts of the area, owing to absence of underground workings, the relative positions of the different rock masses can be determined only by inductive reasoning from known facts in the nearest adjoining explored areas. The representations of such parts are more or less in the nature of surmises and will be subject to correction when those portions of the area are actually explored. That the reader may be able to judge of the relative accuracy of the maps or sections showing the different portions represented, the underground workings have been indicated in the cross sections by full lines when they are in the actual plane of the sections and by broken lines when they are near enough to

this plane to afford accurate deductions. The reader must therefore bear in mind that the geological outlines given are accurate in proportion to their nearness to lines of underground exploration, and that when no such lines are represented the outlines are the result of deduction and are subject to correction in greater or less degree, according to their distance from underground areas actually explored. As no shafts or drill holes have yet reached the underground rock surface beyond the western edge of the area mapped, the uncertainties in the neighborhood of this line are necessarily the greatest of all, but lessen as known workings are approached.

The field observations on which this report is based and the maps and sections by which it is illustrated represent the labors of both authors combined, but the report itself is in the words of the senior author, who alone should be held responsible for its shortcomings.

GENERAL GEOLOGY.

PRINCIPAL FEATURES.

The city of Leadville is situated on a terrace at the foot of one of the western spurs of the Mosquito Range, near the head of the Arkansas Valley. The mines which have made the Leadville district one of the most important producers of silver, gold, lead, zinc, and iron in the West during nearly thirty years are mostly higher up on the spur, some at distances of 2 or 3 miles east of the town. Of late years, however, mining developments have been spreading westward under the terrace deposits on which Leadville stands, and the present map and accompanying text deal almost exclusively with these newly developed deposits.

To those who are familiar with the Leadville region any account of the general structure of the Mosquito Range would be quite superfluous, but as there may be some among the readers of this sketch who have not visited the region a very brief statement of its general features may be useful.

The Arkansas Valley from its head at Tennessee Pass to Salida, where it bends to the eastward, is a north-south depression of geologically recent date that lies between the Sawatch Range on the west and the Mosquito Range on the east. The Sawatch is an oval mass composed entirely of gneisses, granite, and schists, belonging to the crystalline complex on which the Cambrian and later sedimentary beds were deposited. The outcrops of the Paleozoic beds—the older portion of the sedimentary series—almost completely encircle the oval, lying in somewhat different positions on the different sides, but always dipping away from it, showing that it represents an older land mass.

The Mosquito Range is a north-south mountain range whose higher summits rise to elevations of 13,000 and 14,000 feet, consisting mainly

of Paleozoic beds, with some Mesozoic beds along its eastern flanks, between the strata of which an immense amount of igneous rock, in the form of sheets or sills and laccoliths, was forced before the mountains were uplifted. The uplift of the range seems to have been caused by some force acting from the east westward, which has pushed the sedimentary series, with their included igneous intrusions, against the unyielding buttress of the Sawatch massif, compressing them into a series of asymmetrical anticlines, with the steeper side on the west, and, where the limit of flexibility of the rock masses involved was reached, breaking them by a series of north-south faults. During the entire period of wearing down by erosion which has elapsed since the uplift commenced the mountains have been slowly carved into their present form, and the great depression of the Arkansas Valley has been cut out approximately along the old shore line on the east side of the Sawatch.

In that portion of the Mosquito Range in which the Leadville district is situated the igneous intrusions were unusually abundant, and in the dynamic movements which caused the uplift of the range faulting very greatly predominated there over folding, so that the resulting structure, as exposed by erosion, is found to be remarkably complicated, and the difficulty of correctly interpreting this structure has been greatly enhanced by the abundant covering of recent detrital material, largely glacial sands and gravels, which cover the lower slopes.

The Leadville district is thus broken by these faults into a series of fault blocks, in general marked on the surface by higher shoulders on the spurs, which have been locally designated as hills, such as Breece Hill, Iron Hill, Carbonate Hill, Fryer Hill, etc.

FAULT BLOCKS.

As has been explained at some length in the senior writer's original reports on this region,[a] the Mosquito Range, on the western slopes of which the Leadville district is located, is a faulted-up mountain mass of Paleozoic beds, resting on pre-Cambrian granites and gneisses. The faults run in a generally north-south direction, and, as shown where they are exposed in section in the deeper canyon cuts of the range, they are located as a rule along the steeper western limb of an anticlinal fold. The zone or block between two faults should thus have a synclinal structure. The main fault along which the range has been uplifted is called the Mosquito fault, and where it consists of a single fault plane it runs just west of the crest, its scarp forming the remarkably steep western face of that crest, which rises

[a] Abstract of report on geology and mining industry of Leadville: Second Ann. Rept. U. S. Geol. Survey (1880-81), 1882, pp. 201-290. Geology and mining industry of Leadville, Colo.: Mon. U. S. Geol. Survey, vol. 12, 1886.

almost vertically for several thousand feet. In the Leadville region, however, displacement along this fault is distributed on no less than six approximately parallel faults, making as many fault blocks between the Arkansas Valley and the crest. In the original report the structure of the blocks immediately adjoining Leadville, as shown along the line of section E, which runs through the town itself, is given as follows:[a]

In the region under Leadville, or from the western edge of the map to the Carbonate fault, a shallow synclinal; under Carbonate Hill, or from the Carbonate to the Iron fault, a second shallow synclinal; and from Iron Hill eastward a third, in all of which the prevailing dip is eastward, only a small portion of the eastern edge of the basin having a westerly dip. * * * The effect of displacement produced by the faults has been to lift each successive block of ground up to the east of the fault.

Of these three faulted blocks those of Iron and Carbonate hills were defined to a certain extent on either side by outcrops, or by underground workings which had reached what is generally called in Leadville the "contact," or the upper surface of the Blue or Leadville limestone, beneath the great body of White porphyry. This is the important horizon to be determined, because beneath it the miner may commence his search for ore bodies and because the average thickness of the underlying sedimentary formations down to the basement complex of granite is well known. Of the third block, which stretches westward from the Carbonate fault and in which the city of Leadville is situated, only the eastern limit was defined, and that somewhat imperfectly, by the outcrops of Blue limestone along the west face of Carbonate Hill and by the few shafts that had disclosed the Carbonate fault and, at a single point, its parallel, the Pendery fault. To the west of this line the rock surface is buried beneath an accumulation of gravel beds which stretch from the base of Carbonate Hill in a gently sloping mesa, about 4 miles in width, to the Arkansas Valley at Malta, and whose thickness, inasmuch as it had not been penetrated by shaft or drill hole, was still a matter of surmise, although it was estimated to average at least 400 feet. To determine the structure of the underlying rock masses, and thereby to ascertain the extent of possible ore-bearing ground in this western block, constitutes to-day, as it did when the original study was made, one of the most interesting problems connected with the geology of the Leadville district. It is somewhat remarkable, moreover, that, considering the immense amount of underground exploration that has been carried on in the district during the twenty-five years that have elapsed since that time, so little has been accomplished toward determining the conditions beneath the Wash in the western portion of this area. Except that the limit of actually explored ground has been moved 2,000 to 2,500 feet westward, our knowledge of this

[a] Second Ann. Rept. U. S. Geol. Survey (1880-81), 1882, pp. 241-242.

unexplored area remains in very much the same condition that it did in 1881. Inasmuch, therefore, as what can be said of its geological structure will be largely a matter of induction, it will probably be well to review briefly the results obtained by the reasoning employed in making the original report, to note how far they have been found to be correct, and to observe to what extent and in what manner it has been necessary to modify them in the light of the knowledge gained by actual mining work during that period.

The principal modifications that have thus been found necessary in the original indications have to do mainly with two general features, namely, the later intrusive sheets of Gray porphyry and the faults. The probable character of such modifications was in a measure foreseen, but it would have been unwise to attempt to indicate them without more positive knowledge than was then obtainable. Thus, one sheet of Gray porphyry only was indicated as occurring generally about the middle of the Blue limestone, yet as extending, in some places, down to the Parting quartzite. In point of fact more than one such sheet is found at some places, and crosscutting sheets going from one horizon to another are numerous. Although their vertical range is found to extend through all of the sedimentary series, it is still true that the most important bodies occur within the Blue limestone. As will be shown later, these bodies, especially where they cut across the stratification, have exercised an important influence on the precipitation of ore from its solutions.

With regard to the faults, it has been found that, though the lines of outcrop of the principal structural faults have been in the main correctly indicated on the original map, there are in depth many faults of lesser importance, of most of which no indication can be seen at the surface, and that the displacement of many of the greater faults, especially in the lower or western region, has been distributed on a series of parallel fault planes, thus producing step faults. This is most markedly the case where the main fault plane has a reentering bend to the eastward.

In the structure of the interfault blocks folding is found to be less prominent than was indicated, the prevailing dip of the beds being eastward, while it is only in the vicinity of the fault on the eastern side of the block that the strata rise perceptibly toward the east, either in a series of steps where the fault is multiple, or in a steep slope where it is single. There is still enough bending, however, to show the correctness of the author's assumption that the faulting has been a result of the same kind of stress that produced folds, and that the reason that these gentle folds have so soon passed into faults is probably that the intrusion of the great porphyry sheets has made the whole series of beds less flexible and more liable to rupture. Furthermore, the fact that most of the shafts sunk in the Graham Park region have found a contact within less than 100 feet of the depth

indicated on the original map sections proves that, under the circumstances, the synclinal theory was evidently the safest and most logical basis on which to construct the underground structure in this block.

For the unexplored portions of the western or Downtown block it is judged best to follow this general course of reasoning in determining the probable structure of the sedimentary beds that still rest upon the pre-Cambrian basement complex in the region west of Leadville.

As will be seen by an examination of the series of cross sections accompanying the map of the Downtown area, it is in the immediate vicinity of the zone of faults that the principal uplift of the Paleozoic beds has taken place. Where the fault movement has been distributed on several planes this uplift has formed a series of steps. Where the movement was along a single plane, as in the northern part of the Downtown area, there is a distinct western dip of the beds for a considerable distance from the fault plane and a decided indication of an anticlinal structure near the fault. If there are no other important faults to the west of those shown in the underground workings—and we have no right to assume their existence until they are actually proved—the Paleozoic beds may have an approximately horizontal position, with a probable gentle dip to the east. If this assumption be correct, the extent of the ore-bearing horizons to the west is largely dependent on the slope of the rock surface beneath the gravel beds, since if this is steep they will have been cut off by erosion much farther to the east than if it nearly corresponds with that of the underlying Paleozoic beds. In the latter case they would probably remain in very much the position in which they were left by the preglacial erosion of the Arkansas Valley. It is therefore important to understand as well as possible the character and manner of deposition of the gravel, or so-called Lake beds, and the probable condition of the rock surface at the time they were deposited. The next section will therefore present the evidence which has accumulated in late years with regard to these beds and the conclusions which it seems possible to draw therefrom as to the probable extension of the Paleozoic sediments.

QUATERNARY DEPOSITS.

DISTRIBUTION AND CHARACTER.

With the exception of the alluvial gravels of the present streams, the Recent or Quaternary deposits of the Leadville area are of glacial origin. The glacial phenomena of the Mosquito Range in general are so extensive and so remarkably clear and well defined that they are worthy of special study, which the writer would have under-

taken in the original report but that the more strictly economic phenomena were so complicated as to occupy all the time that could be devoted to the work. Their proper illustration, moreover, would have required a special map that would have rendered more cumbersome the already rather large atlas. In the absence of such a map no special chapters were devoted to these phenomena, which thus received a less adequate geological treatment than the facts in his possession warranted. These facts, as read by him, pointed to the existence in this region of two distinct glacial epochs, in each of which there were formed distinct glacial deposits in the Leadville area. It was further assumed that during the first glacial epoch the bed of the Arkansas River, which probably had followed about the middle of the valley, was blocked up by glacial ice and morainal gravels issuing from Lake Creek in the Sawatch Range, which pushed entirely across the valley to the lower slopes of the Mosquito Range, and that in consequence a glacial lake must have been ponded back in the Arkansas Valley above that point. When the water rose high enough to override this barrier it would have found outlet naturally at the lowest point—the extreme eastern end of the barrier—and once started in the readily erodable gravels would have cut down its bed in the same general position, even after reaching the underlying bed rock. This would account for the fact that at the present day the river has cut its bed several hundred feet into the hard rock that forms the eastern spurs of the Mosquito Range at the town of Granite and below. It seemed probable, moreover, that the lowest point in the rock bed of the valley, or the original bed of the Arkansas River, might be farther west, under the morainal gravels that extend out into the valley opposite Twin Lakes. At the time of the original investigation—in 1879–1881—placer mining in the Twin Lakes region was not sufficiently advanced to prove the underground structure by shafts, but, as will be seen later, recent studies have shown that this assumption is probably correct.

At Leadville, and for 6 miles down the valley, the lower slopes of the Mosquito Range have the form of a remarkably regular terrace or mesa, with a slope of $2\frac{1}{2}°$ to $3°$, that extends up to the steeper rock slopes of Carbonate, Dome, and Long and Derry hills, as the shoulders on the respective spurs are locally designated. Similar but less extensive and less well-defined terraces occur on the western side of the Arkansas Valley along the slopes of the Sawatch Range. The surface of these sloping mesas on the spurs of the Mosquito Range were found to be made up of rounded bowlders of the harder rocks that constitute the range, embedded in a matrix of gravel and clay that was locally called Wash. Shafts sunk through the Wash in these areas found under it a varying thickness of finer-grained stratified material, which was approximately coextensive with the

area of the sloping mesa. To this stratified material the name "Lake beds" was given, on the assumption that it had been deposited in the lake supposed to have been backed up in the upper Arkansas Valley by the Lake Creek glacier, while the overlying Wash was supposed to be rearranged morainal material that had been washed down by the floods that resulted from the melting of the ice during the retreat of the earlier glaciers. Over the beds thus deposited the lateral moraines of the glaciers of the second glacial area extend in well-defined ridges, some of them over a mile in length, which are thus readily distinguished from the material deposited during the first glacial epoch.

The method of representation and the treatment of these deposits in the original report was admittedly not scientific nor logical, since on the general map of the Mosquito Range the whole area underlain by Lake beds was represented by the color of that formation; whereas, in point of fact, the surface is in part covered by moraines of the second period, and over the whole is a surface coating of bowlder wash. In the sections, however, the Wash was differentiated from the underlying Lake beds, though in the text the term Wash was made to include all unstratified material, as well as alluvial gravels. The reason for this method of treatment lay in the fact that the maps and accompanying report were primarily designed for the guidance of the miner, and if the Quaternary deposits, including as well the rock slide or angular material resulting from the disintegration of porphyries in place, which often as effectually masks the outcrop as do the moraines or stream gravels, had been represented on the surface map they would have covered so large a portion of the original area that it would have been impossible to represent the structure of the underlying rock in place, which had been carefully reconstructed from a study of the underground workings and was essential as a guide to the exploration of the miner.

In the early eighties, when this report was written, modern physiography, or physical geography, could hardly be said to have taken form, and it was the practice among geologists generally to class as lacustrine beds all recent material that is distinctly stratified, whether it had been actually deposited in still waters or had been washed down along steep slopes into a body of water. The objections to this practice were very forcibly pointed out in 1900 by Prof. William M. Davis, the foremost exponent of modern physiographic methods, in a paper[a] in which he undertook to show that a large proportion of the so-called fresh-water lake deposits in the Rocky Mountain region bear internal evidence of being of fluviatile rather than lacustrine origin—that is, they were spread out by a sort of sheet-flood erosion in moving rather than still waters. Since then

[a] Am. Acad. Arts and Sci., vol. 35, pp. 345-373.

there has been a strong tendency, especially among the younger disciples of the modern school of physiography, to ascribe a fluviatile origin to deposits that might formerly have been classed as lacustrine, in some cases, as it seems to the writer, without giving sufficient weight to conflicting evidence which appealed less strongly to them as physiographers, or students of surface phenomena, than it would to the general geologist.

In the summer of 1904, under the direction of Prof. R. D. Salisbury, studies of the Pleistocene geology of the Sawatch Range [a] were carried on by S. R. Capps and E. D. K. Leffingwell, and in the same summer, at the suggestion of Professor Davis, Prof. L. G. Westgate [b] made a special study of the Twin Lakes glaciated area. In neither case, apparently, was an actual investigation made of the vicinity of Leadville, the conclusions as to the deposits there being probably derived from studies made of their general form from a distance. The conclusions of each of these parties are confirmatory of those of the writer as to the existence of two glacial epochs in this region; likewise as to the fact that the preglacial channel of the Arkansas River lay west of the present river bed, borings in the placer mines west of Granite having shown that the rock surface beneath the gravel slopes westward for a considerable distance, and that the lowest point is probably midway between Granite and Twin Lakes. The observers first mentioned also consider that the ice of the early glacial epoch must have obstructed the valley, since material that could have come only from Lake Creek Canyon was found by them high up on the slopes of the Mosquito Range, on the opposite side of the valley; but they do not admit "that the dam could have been high enough at any time to hold the water up to the level of the high terraces." They agree, however, with Professor Westgate in holding that these higher terraces are of glacio-fluvial rather than of lacustrine origin, basing their conclusions on the assumed facts that the material of the gravels is mainly coarse bowlders, only slightly or not at all stratified, and that no delta structure is observable in them. According to Westgate, moreover, who came to the region from a study of the Quaternary deposits of the Utah Basin, their surfaces have every appearance of alluvial fans.

While the writer is in general accord with the interpretation given by these geologists to the facts observed by them, he ventures to say that if they had made a careful study of the glacial deposits in the vicinity of Leadville, not on the surface only, but underground, where alone the so-called Lake beds can be seen, they might have been led to a different interpretation of some of the facts.

[a] Jour. Geol., vol. 12, November-December, 1904, p. 698.
[b] Jour. Geol., vol. 13, May-June, 1905, p. 285.

LAKE BEDS.

The data gathered by the writer since the original report was made in regard to these beds are regrettably uneven and incomplete, since in great part they are not the result of personal observation but were contributed by those who sunk shafts through the beds, and who, as a rule, not being trained in geological observation, simply noted the change from coarse and structureless to finer-grained and distinctly bedded material. There was, moreover, no opportunity to obtain an extended section of the beds to determine whether they showed delta or flow-and-plunge structure, since the exposures were limited, as a rule, to the diameter of the shaft, there being no inducement to run drifts through these beds, and, owing to their crumbling nature, the shafts were always promptly lagged up. Their upper and lower limits are also necessarily ill defined, since the bowlders of the overlying Wash, being at considerable depth and in moist condition, are decayed to such an extent that they crumble rapidly on exposure to the air, while the underlying rock surface, when of porphyry, as it is generally, is rotted or decomposed for considerable depth, and shows at many places strong evidence of differential movement, especially in the vicinity of the faulted zones.

COMPOSITION.

The prevailing material of these beds is of a pinkish-drab color, resembling a fine-grained marl, and seems to be made up of an arkose of decomposed granite or porphyry. This is the general character of the lower part of the beds, which often contain large fragments in a marly matrix, whose position would be readily explainable as having been dropped from floating ice while the marl was still loose and not fully consolidated. In the upper part there is more clayey material, often with alternating beds of sand. It is said that a drill hole on the mesa south of California Gulch passed through 305 feet of Lake beds, including, in the upper half, forty beds of tough clay, from 1 to 8 feet thick, after traversing 48 feet of overlying Wash and 2 feet of sand.

DISTRIBUTION.

Although the existence of Lake beds beneath the Wash on the lower half of the mesas or terraces that stretch from the hills to the Arkansas Valley has not yet been proved by actual shafts or drill holes, the uniform character of the surface and the fact that borings show that they tend to increase rather than decrease in thickness with distance from the hills favor the assumption that they probably extend down to and perhaps under the present Arkansas Valley as far south as Weston Gulch.

Their upper limit, as shown by actual exploration, is rather irregular; they are not known to extend into the great gorge of the East Arkansas, nor for any considerable distance up Big and Little Evans gulches. Along the west face of Fryer and Carbonate hills their upper limit is practically the Pendery fault, though in the depression of Stray Horse Gulch they are found a little farther east. On the other hand, a thousand feet higher, in Graham Park, there is a singular potholelike depression filled by them to a maximum depth of 300 feet, as shown by the R. A. M., Rialto, Greenback, and adjoining shafts. The upper level of the former mine, at 390 feet from the surface, is driven for over 100 feet in typical Lake bed material, which there rests on Blue limestone. The rock surface at this point has an elevation of 10,261 feet.

South of California Gulch the upper limit of the main body of Lake beds, which along the face of Carbonate Hill had been trending to the west of south, abruptly bends almost due east and runs parallel to California Gulch, from which it is separated by a ridge of rock that reaches in places within 100 feet of the surface of the mesa, while the bottom of the depression in which the Lake beds have accumulated has been found to be 400 to 600 feet below that surface. This embayment of Lake beds on the ridge known as Rock or Dome Hill was originally supposed to extend only up to about the line of the Iron fault, but recent workings in the Reindeer mine have disclosed, just north of the lateral moraine of the second Iowa Gulch glacier, a channel of Lake beds at an elevation of 10,230 feet, apparently reaching still higher up on the southern edge of the hill. This may connect with a patch of similar material on the northwest slope of Printer Boy Hill, whose extent was disclosed by a drift from the lower Printer Boy mine and by the erosion of Eureka Gulch, but of whose form or extent nothing is definitely known. South of Iowa Gulch the Lake beds extend still higher up on the spur known as Long and Derry Hill, the rock surface beneath them at the Continental shaft having an elevation of 10,750 feet. Still farther south, on the spur south of Empire Gulch, their upper limit apparently approaches yet nearer to the crest of the range, until they end abruptly against the granite on the south side of Union Gulch. Their probable extent in this southern region is given as determined during the original survey, since no new data with regard to them have been obtained outside of the immediate vicinity of the working mines in Leadville, but it is assumed to be fairly correct, since no shaft sunk in areas in which they were indicated on the original maps has failed to disclose them.

It is evident that the rock bottom of these beds in these upper regions stands at an elevation that is too high to admit of its having been covered by the waters of any lake that could have been ponded back in the Arkansas Valley by the damming up of the Lake Creek

glacier, since these waters can not probably have reached a height above the 9,700-foot contour. If there had been no elevation of the range since these beds were deposited the only alternative hypothesis would be that they are glacio-fluvial deposits laid down on a gently sloping surface by streams issuing from beneath the melting glaciers, but there is definite evidence of the elevation of the range since that period, and there are other phenomena that are difficult of explanation on the simple glacio-fluvial hypothesis, among them the apparently greater extent of the Lake beds in the bed of the Iowa Glacier than in that of the Evans Glacier. In Evans Gulch their existence has not been noted higher than Cady shaft, opposite Fryer Hill, where the present surface stands at 10,430 feet, while in Iowa Gulch they are found very much farther back than the probable lower end of the glacier, or at points where the present surface is 300 to 400 feet higher. The underlying rock surface, however, stands in an opposite relation, being rather lower on the average under Rock Ridge than in lower Evans Gulch. This condition seems easier of explanation on the hypothesis that the material was deposited along the borders of a lake than simply at the mouth of a retreating glacier.

EVIDENCE OF UPLIFT.

The evidence of continued uplift of the range since the glacial period is both direct and indirect. The indirect evidence is the sudden deepening of the rock surface to the west of the prominent fault planes, producing an abnormal depression in which the Lake beds are first found. Such a sudden down slope of the rock surface was noticed in the original field work, and it was then thought that it might have been produced by wave cutting along the shores of the old lake, but the evidence accumulated since that time tends to show that it always occurs in the immediate vicinity of fault planes, and it therefore seems more reasonable to attribute it to a gradual movement of elevation along these planes, which may very likely be going on at the present day.

The direct evidence of movement observed by the writer was confined to two places, one in the Walcott mine, the other in the Elk mine, both of them along the Pendery fault and in the depression of lower Stray Horse Gulch. In each place the rock face on the foot or east wall of the fault, which stands at 65° or 70°, has been lifted up across the Lake beds, which adjoin it on the west. In the Elk mine the brownish clay that constitutes the Lake beds shows a distinct sheeting parallel to the fault planes, and a selvage of this clay material carries in places a fault breccia that still clings to the limestone foot wall, which it could not have done had this wall constituted a cliff against which the Lake beds were deposited.

The aggregate amount of such displacements can not be accurately determined. In the Elk mine it is certainly as much as 100 feet, and possibly 150 feet. It is probably nearly as much in the Walcott mine, but no Lake beds have yet been found east of the fault in that mine. The amount of difference to be accounted for is, however, less than the present surface would indicate. For instance, the rock surface on the north-south line of Section XII (Pl. VII), a short distance west of the Pendery fault, is not more than 200 feet lower than that at the same distance west of the Dome fault, which is about a mile farther east, while the relative difference of level in the present surface is over 500 feet. On the other hand, the slope of the rock surface may steepen west of this line, to judge from the data gathered on the spur or mesa next south of California Gulch. On this spur shafts and drill holes have reached the contact below the Lake beds at somewhat irregular intervals in an east-west direction for a distance of about 8,000 feet. The angle of the rock slope in this distance, if calculated from its depth at the extreme points, would be 5°, or nearly double that of the present surface, but from a study of the data furnished by those who carried on these underground explorations it would appear that this slope is very irregular. Below the Dome fault it drops abruptly 200 to 300 feet. At the Iron fault it has a comparatively slight drop, and from there to the Revenue shaft, a distance of about 3,000 feet, the figures obtained show no general lowering of the rock surface. Thence westward to the drill hole on the Mike claim, a distance of about three-fourths of a mile, its descent is more rapid, and if continued at the same angle would make the rock surface at Malta 300 feet below the present valley level. It must be admitted, however, that the basis for these determinations is rather uncertain, for the accounts show that beneath the well-defined Lake beds there is a considerable mass of broken rock, which in some places aggregates 100 feet or more in thickness, and renders it difficult to determine tne exact depth at which rock in place was actually reached. While the data are therefore evidently yet too incomplete to enable the geologist to reconstruct with any considerable degree of accuracy the rock surface beneath the deposits of the first glacial epoch, it seems reasonably certain that it has been somewhat disturbed by uplift since that time.

ORIGIN.

As to the manner of formation of the Wash and Lake beds—names which have been retained in deference to established local usage—although it is admitted that the mesa Wash is of probable glacio-fluvial origin, until more conclusive proofs to the contrary are obtained the writer is inclined to the belief that the fine-grained, stratified

material, to which the original report gave the name Lake beds, must have been, in part, at least, laid down under water—possibly in great measure as broad delta deposits—hence that a lake actually existed in the upper Arkansas Valley toward the close of the first glacial epoch. Some part of the higher-lying beds may have been deposited in local ponds or lakes close to points where this finer material was issuing from beneath the glaciers. It is probable that all these lakes were of relatively short duration, and that, when the floods came that accompanied the retreat and more rapid melting of the glacial ice, their barriers were quickly cut through and the lakes drained while the overwash was being carried down and spread out over the surface of the already deposited Lake beds. In narrower parts of the glacial channels doubtless these were in measure eroded away, and such erosion may account for the apparent want of connection between parts of the lower- and higher-level Lake beds at the present day.

SLOPE OF ROCK SURFACE.

As to the slope of the rock surface beneath the Lake beds, it seems probable that its westerly inclination may generally be slightly greater than that of the present surface, as far west, at any rate, as the Paleozoic beds are likely to extend; but that toward the bottom land of the present Arkansas Valley, where granite and gneiss would constitute the bed rock, its slope may decrease rapidly and soon become nearly level, except for its southerly inclination down the Arkansas Valley.

It is probable that a southerly inclination of the rock surface exists in the mesa region also, which should be added to the westerly inclination, for it appears to stand 100 to 200 feet above the 10,000-foot contour, where Evans Gulch bends northward into the East Arkansas Valley, whereas on the banks of California Gulch, in the Maple Street shaft, it is said to be over 500 feet lower. As the surface was probably furrowed to a certain extent by the older glaciers, or by the streams that issued from beneath them, it may be well to consider the probable course of these glaciers as far as it can be determined from the evidence at hand.

POSITION OF THE MOSQUITO GLACIERS.

The amount of erosion that has gone on since the glacial period has been so great that it is not easy to differentiate in the detrital materials found near their present surface those that belong to the first from those that belong to the second glacial epoch, or from those that are postglacial. We get some conception of the amount of this erosion when we consider that the deep cutting of California Gulch is postglacial. Only those gulches that head in glacial cirques or amphitheaters could have carried large glaciers. These were the East

Arkansas, Evans, Iowa, and Empire gulches. The first, though much longer and consequently carrying a larger glacier than either of the others, may be left out of consideration in the present discussion, since there is no evidence that its deposits had much influence on the area here discussed.

The courses of the later glaciers in Evans and Iowa gulches, as quite clearly defined by the lateral moraines which still stand in rather definite ridges, were remarkably straight after leaving the amphitheaters in which they took their rise, in marked contrast with the zigzag course of California Gulch. In Evans Gulch the amount of morainic material deposited along the sides of the glacier was so great that, as the ice melted, new stream beds were formed along the outer edge of these new accumulations of gravel, now known as Little Evans and Stray Horse gulches, which head in basinlike depressions known as Prospect Mountain amphitheater and Adelaide Park, respectively. There is some evidence that in its lower part, after leaving the confining slopes of Prospect Mountain and Breece Hill, the ice spread out somewhat, so as to cover Fryer Hill, but if it extended down as low as the gravel ridge known as Capitol Hill, it was probably bounded by that on the one side and by James Ridge on the other, and did not bend into the East Arkansas Valley as does the present postglacial stream.

The Iowa Gulch moraines extend straight down over the Lake bed deposits for a mile or two below the last confining gorge between Long and Derry and Printer Boy hills, but show no evidence that the ice sheet widened below to any considerable extent. The Empire Gulch glacier has left similar indications with regard to its lower course, but in its upper part followed a more irregular course.

We must assume that the earlier glaciers in their upper courses, where they filled channels bounded by rock slopes, must have followed the same course as did the later glaciers. To judge from the amount of material they left behind they would appear to have been more extensive than the later glaciers, but we can not now distinguish their lateral moraines. It is probable that the earlier Evans Glacier entirely overrode Yankee and Fryer hills and that in its lower course a part, possibly the greater part, flowed down the depression of lower Stray Horse Gulch, between Carbonate and Capitol hills, since the evidence gathered during the preparation of the present map shows a depression in the rock surface under this part, as indicated in the sections. Whether the eroding agent was ice or water, its channel, on leaving the steeper hill slope, evidently bent to the southwest, running about parallel to a line drawn between the Sixth Street and Cloud City shafts. Along this channel relatively less of the Paleozoic beds would be left than on either side, and to this extent more ore-bearing

rock material would have been removed, but the channel was probably so shallow that the amount thus carried away would not have been sufficiently large to influence essentially the prospective value of the ground.

ECONOMIC DEVELOPMENT.

Before proceeding to the description of the present geological structure of the Downtown area, it may be well to review briefly the progress of knowledge with regard to it as illustrated by the successive mining developments within the area. The reader's understanding of this review will be much facilitated by frequent reference to the map and sections. The area covered by the map is approximately 1 mile in length by two-thirds of a mile in width, the longer dimension being from north to south. The western limit runs diagonally across Harrison avenue, from a point just north of its junction with Chestnut street northward to the southwest corner of East Thirteenth and Hemlock streets, while the eastern boundary runs from the top of the western slope of Carbonate Hill to the southwest point of Fryer Hill. The map thus includes practically all of the town east of Harrison avenue and south of the Denver and Rio Grande Railroad station.

At the close of Survey field work in the summer of 1881 underground exploration was practically confined to a zone about 1,000 feet wide along the eastern or upper edge of the area mapped, and the structure, as deduced from these explorations, was determined as follows:

At the northern end of this zone, on the west point of Fryer Hill, White porphyry was found both above and below the Blue limestone, or the vein material which replaced it, this being within the northwest-southeast belt along which the White porphyry sheet cuts diagonally across the Blue limestone, thus splitting it into two or more wedge-shaped bodies. Furthermore, a sheet of younger Gray porphyry cut across both, and at some places assumed a dikelike form. This whole series of formations was found to rise gently westward toward the west point of Fryer Hill. White porphyry had been found under the Wash to the west of this, and it was assumed that it represented a western dip in the formations beyond an anticlinal fold.

In the depression forming the two Stray Horse gulches, between Fryer and Carbonate hills, the few shafts that had been sunk furnished but little definite information with regard to the structure, beyond the indication that it is very irregular and broken. In both these gulches the rock surface is buried beneath 50 to 100 feet of Wash. On Carbonate Hill, however, the rock formations, which were covered by only from 6 to 10 feet of rock slide, were found to be quite regular, striking a little east of north and dipping southeast-

ward at angles of 12° to 20°. The normal series here represented is given in the following table, in descending order:

Local name.	Geological age.	Character of rocks.	Average thickness.
			Feet.
White porphyry	Pre-Cretaceous	White rhyolite porphyry	800
Blue limestone	Lower Carboniferous	Blue-gray dolomite	200
Gray porphyry	Pre-Cretaceous	Gray monzonite porphyry	50
Parting quartzite	Devonian	Coarse quartzite	30
White limestone	Silurian	Drab siliceous dolomitic limestone.	160
Lower quartzite	Cambrian	Mostly white quartzite	160
Granite	Basement complex or pre-Cambrian	Granite and gneiss	

Of these the igneous rocks are necessarily the more liable to vary, both in horizon and in thickness. The Gray porphyry is generally in a single sheet, in the body of the Blue limestone, but may occur in more than one sheet, and be found anywhere from the top to the bottom of this formation. Erosion has removed more or less of the White porphyry, which is consequently at its greatest thickness at the eastern limit of the fault block, and farther west has been thinned by erosion until, along the base of the hill, the Blue limestone is exposed beneath the thin covering of porphyry slide. It was in following this limestone eastward on the dip that the Carbonate Hill mines found their great bodies of carbonate of lead and chloride of silver in a matrix of impure iron and manganese oxide, resulting from the oxidation of pyritous ores. West of the line of the Carbonate fault the surface is generally occupied by White porphyry, over which is a covering of Wash that thickens rapidly with increasing distance from the steeper slope of the hill. From information derived from the few shafts already sunk in this zone it was inferred that toward the west the formations descend either in a general westward slope or in a series of sharp folds and faults, and that, as the ore body disclosed on Carbonate Hill might reasonably be expected to extend in that direction, the region was well worthy of exploration.[a]

As regards the best method of developing this area, it was foreseen that under the deepening Wash an enormous amount of water, draining from the adjoining hill slopes, would necessarily be found, and the suggestion was offered that a combination of property owners be formed to sink one or more deep shafts well out on the mesa slope, which would not only determine the general slope and character of the underlying rocks but would drain the intermediate ground, and thus facilitate mining over the whole area. If this were found impracticable, the next best plan, it was suggested, would be to sink shafts on the lower slope of Carbonate Hill and gradually follow the contact westward. The latter plan is the one that has practically been followed, but the consequent development of the region has proceeded much more slowly than it would have under the first plan,

[a] Second Ann. Rept. U. S. Geol. Survey, pp. 281-282.

for, as explained in the first report, each fault block as a rule constitutes a separate hydrostatic basin, within the limits of which there is so free a circulation of underground waters that the rise or fall of the ground-water level in one mine is sympathetically felt in all the others within the block or basin. Thus, as each new shaft to the westward reached the ore horizon (as a rule at a deeper level than the previous ones), it was found that it drained the water from all the surrounding but higher-lying levels, and the enterprise was penalized with an undue proportion of the very serious expense of pumping water. This was later remedied by the association of the important mine owners on the community of interest principle, by which it was arranged that each should bear his proportionate part of the total expense of pumping. Even then, however, men who desired to explore still lower ground sometimes found it difficult to gain admission to the pumping association, and thus were prevented from sinking below the level reached by the mines already working, unless they were willing to pump for the entire region.

The sinking of a 500-foot shaft to reach a horizon in which there was only a possibility of finding ore was already a sufficiently hazardous enterprise, but when the search for ore was limited to a given level, and the seeking for it below that level involved such an enormous additional expense, it can be readily conceived that the risk was almost prohibitory.

It is not possible to give the exact order of development of the various mines of the Downtown area, as the writer's visits were made at irregular intervals, between which it sometimes happened that a mine had been opened, worked out, and closed; in many cases, however, to be reopened later. Among the earlier mines was the Pocahontas, whose shaft traversed about 100 feet of Wash and about 180 feet of White porphyry before reaching the Blue limestone. Its ore was found on various shelves of the fault zone, the shaft having reached the limestone near the Pendery fault. The Gray Eagle followed closely, also working ore along the upper contact in the fault zone.

Next, the group of the Dillon, Elk, and Hussey mines found second contact ore between Gray porphyry and Parting quartzite within about 200 feet of the surface, but this ore was sharply cut off on the west by the Pendery fault, and the mines were in time closed down without getting ore at lower levels. The Walcott and Hibschle mines, a little farther northwest, found ore at the same general depth, also immediately under the Wash, but this ore, owing to the general rise of the formations toward the north, was at a lower geological horizon, namely, near the bottom of the White limestone and in the Transition beds at the top of the Cambrian.

South of the Pocahontas, on the same general level, the Weldon and Glass-Pendery shafts were sunk through Wash and White porphyry ıd cut the Pendery fault.

By these explorations the general position of the fault zone was fairly well defined and shown to be considerably west of the Carbonate fault, as located on the early maps, but the depth of the limestones farther west was still uncertain until the Sixth Street shaft was sunk within the streets of the city, about 1,000 feet west of the Pendery fault.

The location of this shaft was unfortunately chosen in that it found the rock surface in the depression that follows the general course of Stray Horse Gulch, consequently abnormally deep. It thus drained the water from all the region around, which entered in such volume that for a long time it could not be handled, and the mining of the fine ore bodies that were afterwards found in its neighborhood was delayed for a number of years. It established the fact, however, that the Blue limestone was still uneroded at that distance to the west, though its elevation was but little below that at the base of the Pendery fault.

The next pioneer shafts were the Bon Air and Bohn, sunk a little farther west and considerably south of the Sixth Street shaft. They found the rock surface over 1,000 feet higher, but the limestone contact a little lower. It was thus proved that the latter lies fairly flat in a broad shelf to the west of the Pendery fault, and it has been on this shelf that the mining of the last decade has been mainly conducted, while in a general way the work has progressed eastward toward the faults rather than in the opposite direction. Thus, at the south the opening up of the Weldon No. 2, Midland, and Can mines has followed that of the Bon Air and Bohn; at the north the developments in the Coronado and Capitol have been the result of the sinking of the Sixth Street shaft; while in the central region the Penrose, the first shaft sunk there, has been followed by the Midas, Bison, and Starr to the east and south.

The next step westward was made by the Cloud City shaft, which was sunk in the midst of the city blocks and which, after passing through 425 feet of Wash and Lake beds and a few feet of White porphyry, came into the westernmost fault yet discovered, which has been called the Cloud City fault. Here again the water has been an obstacle to rapid development, for the Cloud City shaft was sunk near the eastern boundary of the company's property; therefore, to develop the main area, it was necessary to sink the shaft deeper by the amount of the throw of the fault. This was, however, impracticable, until the owners gained admission to the pumping association, which for some years was refused them.

PRESENT CONDITIONS.

As the geological indications given on the accompanying maps and sections are entirely dependent on data derived from mine workings, it may be well to state in some detail the condition of these workings

at the time the last observations were made, namely, in the summer of 1905, since subsequent developments may furnish ground for modification of the conclusions reached, and no one understands better than those who have carried on this work the great uncertainty that attends the determination of probable structure in a region like this, in ground that has not already been opened and examined. The general order followed in making this statement will be from the east westward, the areas along the eastern border of the map being first considered.

Carbonate Hill.—Of the southeast corner of the area—that is, Carbonate Hill east of the Carbonate fault—but little knowledge has been gained by actual observation since the original survey, as most of the large mines were closed down when the periodical visits were made, and the working maps of but few of them were available for study. In later years work in this area has been done mostly by leasers who do not keep up regular surveys, and the data obtained are oral, and hence somewhat vague and uncertain. The structure in this area is, however, relatively regular, and in spite of this uncertainty the formation outlines should be fairly accurate. Of the distribution of ore bodies, on the other hand, so little is accurately known that their representation may be considered to be only a rough approximation.

Fryer Hill.—On Fryer Hill, a portion of which is represented on the northeast corner of the map, there are the same grounds of uncertainty as on Carbonate Hill, and the structure is not simple but extremely complicated, owing to many irregular intrusions of both Gray and White porphyry. No underground examinations were made in this area, and the only new information furnished is with regard to the rocks passed through by a few new shafts, such as the Clark and Colorado Chief No. 2.

Stray Horse Gulch.—Between Fryer and Carbonate Hills lies an area concerning whose structure there is still greater uncertainty, for it is a region where both intrusive porphyries apparently cut across the sedimentary strata instead of conforming with their bedding, and on this account the indications on the earlier map were confessedly tentative. Of the mining that has been done in later times few reliable records have been obtained, the complications of structure having evidently been a serious drawback to the operations there carried on. The indications in this region must therefore be regarded as merely showing a possible solution of the theoretical conditions assumed.

Below Carbonate fault.—With regard to the belt of ground immediately below the Carbonate fault, and thus within what is here called the fault zone, there is also some uncertainty, since the mine openings there were made in the intermediate period between visits, and many of the facts with regard to them have been obtained orally rather than by personal observation. This applies to such workings as the Jolly, Buckeye Belle, Forsaken, and those on the lower part of the Waterloo,

Morning Star, Evening Star, Crescent, and Catalpa claims. In this region of complicated faulting the data obtained have furnished a series of structural problems which the added uncertainty as to correct location of some of the abandoned shafts has rendered it very difficult to unravel. While the solutions presented by the map and sections are thus subject to possible errors of detail, it is believed that these will not affect the correctness of the general conclusions arrived at.

Southwest slope of Carbonate Hill.—The steeper slope of the southern end of Carbonate Hill made by the cutting of California Gulch, not being covered by Wash, is considered as an area of outcrop. In point of fact, however, this surface is actually covered by rock slide to such a depth that only where artificial cuttings have been made can the character of the underlying rock be determined. Such openings are irregularly distributed, and the few that had been driven to any considerable depths were wholly inaccessible, so that while there is an appearance of duplication of outcrops, which suggests a fault, in the absence of such direct proof of its existence as would be shown by its crossing by a drift, none has been indicated.

Bench below Pendery fault.—For a thousand feet or more west of the Pendery fault the upper surface of the Blue limestone, except where it is upturned against the fault plane, stands at an elevation between 9,750 and 9,850 feet, so that, neglecting its minor undulations, it may be considered as a broad bench broken on the west, and through part of its length, by the Cloud City fault. It is on this bench that most of the mining of the last decade has been carried on, and from the workings of these mines have been derived most of the facts of personal observation on which the present report is based. These include, commencing at the north, the workings of the Capitol, or Northern, Coronado, Sixth Street, Midas, Bison, Gray Eagle, Penrose, Starr, Bohn, Bon Air, P. O. S., Midland, and Can shafts, which constitute a horizontal area of about 100 acres of almost continuously explored ground.

Outside area.—Outside of these connected workings the data as to underground structure have been derived from disconnected workings or isolated shafts of which only a small number could be personally examined.[a]

On the north the limestone contact has been reached by the Newell (P), Villa, and Delante No. 2 shafts within the area of the map, and the Delante No. 1, Seeley (P), Jason, Neptune, All Right No. 2 (P), Fairview No. 4 (P), Stumpf, and Hofer shafts on Poverty Flat, beyond that area; on the west in the Cloud City (P), Home Extension and A. V. (P) shafts; on the south along California Gulch in the Toledo Avenue (P), California Gulch, Valentine, and Maple

[a] To the names of such as were personally examined a P is appended.

Street shafts. The latter, on the north bank of California Gulch, between James and Maple streets, is the westernmost point at which the depth of the limestone contact had been reliably determined, being about 2,100 feet west of the western edge of the area mapped. A little farther south a drill hole sunk on the Mike claim is said to have reached the contact, but the record of rock material passed through is somewhat puzzling and difficult to construe.

STRUCTURAL GEOLOGY.

The following verbal description is intended to supplement the information given by the accompanying maps and sections, so as to enable the reader to fill the gaps left between sections and to appreciate the relative proportion of known facts and of inductive reasoning which form their basis in different parts of the area. He should keep before his mind the fact that the surface maps represent the actual rock surface from which it is assumed that the detrital covering of Wash and Lake beds has been removed. The position and approximate thickness of this covering is given on the sections. In this verbal description the faults will be described first and afterwards the successive cross sections and different mines, or groups of mines.

FAULTS.

In describing the effect of faulting on a series of beds, as deduced from the relative position in which they are now found, more than one term may be used to express the amount and character of the movement. The throw is, properly speaking, the maximum amount of movement along the plane of the fault. Such a throw may be resolved into three factors or components:

(1) A vertical component, which is the vertical distance a given point has been raised above its original position, and which is called the vertical separation.

(2) A horizontal component, which is the horizontal distance that such a point has been moved along the plane of the fault and which is called the lateral separation or offset.

(3) The angle which the plane of the fault makes with the horizon and which is called its dip.

Of these the offset can rarely be determined, though it is often evident, from the indication of the striæ on the walls of the fault, that the movement was not strictly vertical, and that, hence, there must have been a lateral component. For practical purposes, in the present case, the vertical component and the dip, as given by sections along a vertical plane, such as those here presented, furnish the essential facts. On such sections the amount of throw represented with a given vertical separation is dependent on the angle of

dip of the fault, being equal to the vertical separation if the fault plane is vertical, but increasing as its angle of dip departs from the vertical. On the other hand, with a given angle of dip the vertical separation naturally increases with the throw. The angle of dip in the normal faults in this region is observed to vary from point to point, but as observations on the actual fault planes are generally confined to one or two points the rest of the fault must be drawn at an arbitrary angle, which is here assumed to be about 65°, the one most commonly observed. In some cases the angle of dip has been found to shallow somewhat with depth. Such shallowing is not sufficiently uniform to justify its assumption as a general rule. On the other hand, the vertical separation, being dependent on the relative position of certain given rock formations in the mine drift on either side of the fault, can be determined with considerable accuracy for the sedimentary beds, though the position of the intrusive sheets of Gray porphyry is more uncertain, as they are liable to change in geological horizon within comparatively short distances. Hence, on the sections the representation of vertical separation is generally a closer approximation to the truth than that of the amount of throw.

Where the fault is distributed on several planes the amount of displacement on a given plane is necessarily less than when the total movement is on a single fault plane. For the whole fault zone the vertical separation varies from 600 to 1,000 feet, but, as will be observed, the amount of throw on the same fault has a much wider range of variation.

The faults have been represented by a single line on the sections for the reason that, though the amount of fault material involved in their movement may in some cases reach a thickness of 50 feet or more, it varies very much with the amount of throw, the character of rock passed through, etc., and is sometimes less than the thickness represented by a line on the scale of these sections.

Pendery fault.—The Pendery is the important fault of the area, since it is traceable continuously across its entire extent and probably extends for considerable distances beyond it in either direction, thus constituting one of the great faults of the region. Its throw at either end, where it is a single fault, is 1,000 to 1,200 feet, as determined by the sections, which is probably a maximum. Between the Can and Walcott No. 2 shafts the throw indicated on the Pendery fault is very variable, because its movement is distributed on a number of minor fault planes. The number of these minor faults is greatest in the vicinity of the parallel 39° 16′, where, as may be observed, the outcrop of the Pendery fault has a marked reentering curve to the west.

In such a reentering curve on the Iron fault the throw is also found to be distributed on a number of minor fault planes or step faults.

In the case of the Pendery fault a possible reason for the reentering in the outcrop may be found, however, in the probable preexistence of an earlier monoclinal fold, with sharp drop toward the south, which is known to run in a general east-west direction through the northern end of Carbonate Hill, just north of the Wolftone, Maid, Seneca, and Harker shafts, and which, as will be explained later, had an important influence on ore deposition.

Carbonate fault.—This fault may be considered as one of the minor faults of the Pendery fault zone. Between the Carbonate and Ætna mines it has a throw of 250 to 300 feet, but the amount of throw decreases toward the north to such an extent that it can not be traced continuously. What is assumed to be its continuation was found at about 175 feet west of the Harker shaft, where its movement is reversed, its downthrow being eastward and its displacement not over 50 feet. Beyond that it has not been proved, and it is doubtful if it extends much farther as a continuous plane of movement, though other small faults are known to exist in the Stray Horse Gulch depression. To the south it is represented as connecting with the Pendery fault by a sharp bend westward. It has not been actually proved to have this bend, which is assumed as the most probable solution of the facts observed in the adjoining mines. It is possible that it continues more directly south and gradually dies out. Faults of small throw are likely to have a limited longitudinal extent, and it is probable that there are other faults of small throw in the region to the south on which such movement has been distributed. One such fault of about 150 feet throw has been cut just east of the Toledo Avenue shaft, in California Gulch, which can not be surely connected with any other, though it seems probable that it may be the same one struck by the Revenue shaft on the mesa south of California Gulch. Small faults of less than 100 feet throw were also found in the Modoc and Thespian ground, under the top of Carbonate Hill.

Niles fault.—The Niles fault, so named because it was best shown in a drift from the Niles shaft, is intermediate between the Carbonate and Pendery faults. Toward the north it was cut in the Buckeye Belle and Jolly workings, but has not been proved farther north, where it probably passes into a slight fold. Its supposed continuation southward passes into the St. Mary, Washburn, and upper Weldon ground. That it actually connects with the Pendery fault, as indicated on the map, is not proved.

Wildcat faults.—Curving faults in the Wildcat ground, indicated on the map as connecting, respectively, the Carbonate, Niles, and the Pendery faults, have not been determined by actual observation, as they are in ground which was inaccessible at time of visit. They are given as the most probable explanation of the relative position of the different formations as deduced from verbal information.

Bison fault.—The Bison fault, indicated on the map, is shown only in the workings of the Bison mine. Its indicated connection at either end with the Pendery fault is assumed, not observed. It has a normal westerly dip and is cut by the shaft and also by the drifts of the mine to the west of the shaft. There is another fault shown by these workings that has a reversed or easterly dip, so that the wedge-shaped block of ground included between this and the Pendery fault has dropped instead of being uplifted. It is indicated as a cross fault between the Bison and Pendery fault. All the complications of structure disclosed by the workings of the Bison mine could not be indicated on the present scale of drawing, nor were the workings themselves sufficiently extensive at time of visit to admit of their being fully worked out and explained.

Weldon fault.—The Weldon fault, so named because its movement apparently reaches a maximum in the Weldon mine, is of a rather common type, and may be called a monoclinal fold fault, since it belongs to a class of faults that usually pass into a monoclinal fold at either end. They are generally of small throw—in this case not over 100 feet—and stand at rather steeper angles than the normal faults; hence if they extend far enough in depth they will probably join the main fault, as is shown in Section X (Pl. VI). This is, however, a theoretical deduction not proved by actual observation, and it is possible that their vertical extent is as limited as the horizontal has proved to be; hence, in the sections, many of these faults have not been continued up to the rock surface. South of the Weldon mine the Weldon fault has been observed in the Midland and P. O. S. ground with very much diminished throw. Farther north it was seen in the Pendery, Gray Eagle, and Bison areas, but whether it extends to a connection with the Pendery fault in the Midas ground was not determined. Other fold faults of comparatively small extent have been observed which are not indicated on the surface map, and some of these do not cross the plane of section. In these the throw is but slight and the fold is not traceable for any considerable longitudinal extent.

Cloud City fault.—This fault is clearly shown in the Cloud City shaft, where it has two and possibly three planes of movement within a horizontal width of about 50 feet. The workings disclose a westward dip of the contact west of the fault, but the amount of its throw had not yet been proved. Its southward extent is probably very limited. Toward the north, it is assumed, it connects with the fault that passes through the Sixth Street–Coronado ground, though this connection has not been proved. In the lower workings of the Coronado it appears to split, one branch going north toward the synclinal fold in the Capitol ground; the other bending eastward and probably passing into a fold in like manner. It is noticeable that the

continuation of the latter line up Little Stray Horse Gulch marks a rise in the beds toward the north. It seems improbable that any considerable faulting of the beds will be found west of the Cloud City fault, though some small fold faults probably occur. In view of its limited longitudinal extent and small throw, which is probably nowhere much over 200 feet, the Cloud City may be classed as a fold fault.

GRAY PORPHYRY SHEETS.

The sedimentary formations are comparatively uniform in thickness and always retain the same relative position, so that if the depth of the top or bottom of one of these is known one can calculate with a fair degree of accuracy that of the others beneath the uniform covering of White porphyry. One can never know beforehand, however, exactly where the Gray porphyry sheets are to be found; yet in the search for ore it is extremely important to locate them, for experience has shown that in their vicinity important ore bodies, generally known as second-contact bodies, are liable to occur. The only available guide in searching for them in unexplored ground is the knowledge of the position they occupy in ground that has already been opened. The most common position of the Gray porphyry intrusion, when it is a single sheet, is about the middle of the Blue limestone, and its average thickness may be taken at about 50 feet. This is the position given it in those parts of the sections where there is no ground furnished, either by actually observed data or by inference, for placing it elsewhere. Its most pronounced departure from this average position is in the middle ground, in the vicinity of Penrose and Midas shafts, where it rises in places to the top of the Blue limestone, and at several points apparently splits, sending off shoots at lower horizons, since two or more distinct sheets are found at certain points. Section XII (Pl. VII) gives the most comprehensive view of the general distribution of the Gray porphyry sheets, from which it is seen that from near the Lazy Bill shaft northward to the line of the Sixth Street shaft it is near or actually in contact with the overlying White porphyry, and that within this extent there are several small sheets at some distance below it. North and south of this area it descends in horizon quite abruptly in the Sixth Street–Coronado ground, and more gradually toward the south, through the Weldon, Bon Air, and Bohn claims. Near the latter shaft there is another vertical body, which is assumed to be an offshoot from the main sheet, though its actual junction with it could not be seen. To the east of the Penrose shaft the main sheet descends in horizon somewhat abruptly in places, and in the Bison ground it apparently forms two sheets, though, owing to the extremely complicated faulting in this ground, one can not be sure of the original position of the different

beds. Farther northeast, beyond the Pendery fault, in the Elk-Hussey ground, it lies a comparatively short distance above the quartzite. Still farther east, in the Stray Horse Gulch depression, it cuts across the other beds, at some places in such thickness that the possibility is suggested that there may be a vent in that region through which it has come up through the underlying Archean. Farther north, in the Poverty Flat region, and farther west, beyond the Cloud City fault, it has not yet been cut by any shafts or drill holes, and although this is not absolute proof of its nonexistence, it has been indicated on the respective sections as wedging out, since they are drawn on the principle of indicating only those features of whose existence there is some positive evidence, either direct or indirect. Thus on Section XI (Pl. VII), midway in its extension beyond the limits of the map, the Valentine shaft found 45 feet of Gray porphyry between White porphyry and Blue limestone, while the Maple Street shaft, at the western extremity of the section, went 135 feet into Blue limestone without cutting any Gray porphyry. On this ground the Gray porphyry sheet is represented as wedging out midway between the two shafts.

There is as yet no absolute evidence of Gray porphyry sheets below the Parting quartzite in this area except on Fryer Hill, in the Colorado Chief No. 2 shaft. On the original map a sheet was indicated in Silurian limestone at its crossing of California Gulch on the evidence of material supposed to come from a couple of small shafts in that neighborhood, but it is now thought that there was some error in the location of these shafts or in the determination of their horizon and that there is no sufficient reason for supposing that such a sheet exists. Although comparatively few drill holes have been sunk to the underlying granite west of the Pendery fault, and the evidence is therefore negative for a considerable part of the area, it is probable that there is no general Gray porphyry sheet in these lower horizons.

ORES OF THE DISTRICT.

GENERAL CONDITIONS.

As these ores, so far as developed when the present examination was made, have practically the same mineralogical composition as those which were fully described in the original report, no special study of them has been attempted during the various visits to the district made for the purposes of this revision. Indeed, all the time that could be devoted to underground work in each case was taken up in searching for facts bearing on geological structure and on the genesis of the ore bodies.

Up to the time of the last visit the developed ore bodies lay entirely within the oxidized zone and were all found at horizons above the

Parting quartzite except a few bodies at lower horizons that, being laid bare by the scoring off of the overlying beds in the Stray Horse Gulch valley depression, were found immediately below the Wash. The existence of sulphide ores in the White limestone just east of the Cloud City fault in the Penrose, Sixth Street, and Coronado grounds had been determined by a series of diamond-drill borings from the 600-foot levels, but these ores had not yet been reached by mine drifts. From their analogy with other sulphide ores of the district, it may be assumed that these consisted originally of diversely shaped masses of pyrite and marcasite, with a varying admixture of zinc blende and galena irregularly distributed through their mass and at some places following rather ill-defined lines.

METHOD OF OXIDATION.

The process of oxidation, being carried on through the agency of waters coming from the surface, acts primarily on the upper surface of the sulphide body, but when the latter is exceptionally dense and of considerable size the oxidation may proceed from the sides and even from the under surface inward before the center of the mass is completely altered. The first step in the process is its gradual disintegration into a sand of loose crystalline grains, the faces of the crystals becoming more and more pitted as the process advances. The metallic sulphides first become sulphates and gradually suffer further changes until they reach a stable form. During these changes there must have been a certain amount of transmigration of materials involved, which tended to enlarge the area occupied by the ore bodies, though, as a certain part of the altered matter must have been entirely carried away, the actual weight of the oxidized ore is probably less than that of the original sulphide.

Iron.—The first product of the alteration of the iron sulphides is the hydrous sulphate, melanterite, or iron vitriol, which can be seen in some places among the partly altered grains of pyrite. This is, however, an extremely unstable compound and may change to a basic ferric sulphate, which is apt to settle near the base of the ore body in the form of an ocherous yellow clay, carrying considerable silver, lead sulphate, and other minerals. In greater part, however, it becomes the hydrous oxide—limonite—which penetrates and replaces the surrounding limestone and with a varying admixture of other materials, principally silica and manganese dioxide, forms the low-grade ore, or vein material, locally known as iron.

Zinc.—The hydrous zinc sulphate is presumably more soluble and less stable than the corresponding iron sulphate. In Leadville, like the gypsum, which should have been formed by the reaction between iron sulphate and limestone, it is practically absent from the oxidized zone and must have been carried away in solution or redeposited as a

sulphide below the zone of oxidation. It has, in fact, been observed that the sulphide ores are much richer in zinc blende immediately below the limit of oxidation than elsewhere. Dechenite, or the vanadite of lead and zinc, is also found as an accessory and rather rare mineral.

Lead.—Lead minerals being less soluble than those of the other metals, many unaltered kernels of the sulphide, galena, are found in the midst of oxidized ore bodies. Around such kernels the normal process of alteration through the sulphate, anglesite, to the carbonate, cerussite, can generally be observed, but throughout the mass of the oxidized ores the predominant lead mineral is cerussite, in which no anglesite is observed. Pyromorphite, the chlorophosphate of lead, is occasionally found in the richer bodies.

Two general forms of lead carbonate ore are recognized by the miners as "sand carbonate" and "hard carbonate." The former are aggregations of imperfectly crystalline granules of cerussite, the largest bodies of which are as a rule found immediately under or near the porphyry contact. They are composed of remarkably pure carbonate of lead, some of them white, but most of them somewhat stained by metallic oxides, and are evidently the product of the alteration in place of considerable bodies of galena. The hard carbonate is a jasperoid, or siliceous replacement, impregnated with cerussite, in which the latter may have been slightly transposed during alteration. It is irregularly distributed through the mass of iron vein material, but is especially abundant around large bodies of sand carbonate. As a rule, the sand carbonates contain the smallest amount of silver in proportion to the lead present—say, 20 to 40 ounces of silver in ores that run 50 to 70 per cent of lead; whereas the hard carbonates generally carry about an ounce of silver to each unit of lead.

The galena in the oxidized ores is exceptionally rich, often running several hundred ounces to the ton, which is apparently due to secondary enrichment.

Silver.—The amount of silver in the original sulphide ore is so small that its presence can not be detected by the eye. It is probablv in the form of sulphide, but whether mechanically mixed with the other sulphide or in actual combination has not been determined. From the few analyses available it would appear to be more abundant in the zinc blende and galena than in the pyrite, though it is very generally present in the latter. In the unaltered and enriched ores, while galena and zinc blende may carry 50 or more ounces per ton, the pyrite would not be expected to assay more than 10 ounces.

In the oxidized ores, probably owing to the ready solubility of its sulphate, silver seems to have been the most generally transposed

metal next to zinc, for it is universally present in small amounts in all vein material, and the country rock around the ore body is often impregnated to a slight extent. Its stable and visible form is the chloride, which, in the Leadville ores, usually has a slightly greenish color and contains a small amount of bromine and iodine. It usually lines cracks or joints in the other minerals, but is in places concentrated in small bodies, in some of which a crystalline structure is distinguishable.

Native silver is occasionally found in the richer ore bodies, especially at the upper contact. In general distribution the tenor in silver in the oxidized ores diminishes with depth. The upper-contact bodies as a whole are the richest in silver, the second-contact bodies having on the average a slightly lower tenor, while at lower horizons the ore is of distinctly low grade. Under favorable conditions exceptionally rich concentrations may be found at either horizon, but these are more common at the upper contact than elsewhere.

Gold.—The small amount of gold found, which in the ores in this part of the district rarely reaches more than a few hundredths of an ounce per ton, is intimately associated with the silver. In some parts of the district traces of telluride have been found, which would suggest a combination with that metal, but nothing can be definitely determined with regard to the constitution of a metal that occurs in such infinitely small amount.

Manganese.—There is a notable difference in the relative amount of manganese found in the sulphide and the oxidized ore deposits of the Leadville district. The silicate and carbonate (rhodonite and rhodochrosite), which are the usual mineral forms in which manganese occurs in original ore deposits, are notably absent from the sulphide bodies at Leadville. Examination of a large number of analyses of sulphide ores has shown, moreover, that the amount of manganese is rarely over 2 per cent, and that the average is probably not over 1 per cent. In the oxide zone the great mass of the iron vein material contains a varying percentage of manganese oxide, and with increase in the proportion of this metal the whole mass assumes a brown-black color and is known to the miners as black iron. As a general rule the black-iron deposits seem to be more abundant in the upper part of the deposits near the contact with an overlying porphyry sheet, the manganese decreasing with depth. Large areas of such bodies carry from 15 to 25 per cent of manganese, with 20 to 30 per cent of iron, and when so situated that they could be very cheaply mined considerable shipments of such ore have been made from time to time to steel works as far east as Chicago.

The question which naturally presents itself is, What is the reason for such an abnormal increase in the percentage of manganese relative to that of iron during the alteration from sulphide to oxide? The

explanation which at first suggests itself, and which has been advanced by Mr. Blow, is that an additional amount of manganese oxide has been leached from the overlying porphyries by surface waters, since most of the porphyries contain small percentages of manganese, and in a variety of White porphyry, called by the miners "forest rock," it is visible in abundant dendrites on joint cracks. The apparent greater abundance of manganese immediately under porphyry contacts, which would have been the first reached by descending waters, favors this hypothesis. On the other hand, analyses show that porphyries which carry manganese contain an even higher percentage of iron, so that it would seem further necessary to prove that manganese oxide is either more readily dissolved or more readily precipitated than iron oxide. Vogt,[a] in writing on the bog deposits of manganese, whose origin in Sweden and Norway he ascribes to the leaching of eruptive rocks, advocates the former idea, reasoning that in acidic eruptives the iron is most commonly in the form of insoluble oxides, such as magnetite, ilmenite, etc.; whereas manganese occurs in the silicates, whose decomposition yields a soluble product. It is a very generally observed fact, however, that in deposits containing oxides of iron and manganese, associated together, the manganese ore extends only to a limited distance below the surface, and that the proportion of iron increases with depth as that of manganese diminishes. Whether such deposits are original or secondary, they have in most cases reached their present condition through the agency of surface waters, whence it may be inferred that manganese oxide is more readily precipitated and more stable than iron oxide under such conditions.

In the present case, to prove that there has been an actual addition of manganese to a given deposit during oxidation it would be necessary to determine the total amount present in the ore before and after such oxidation, which is manifestly impossible. If there has been such an addition the manganese is likely to have been derived from the porphyries. In any event, however, some selective action in the relative precipitation of the two metals seems necessary to account for their present relative distribution.

EARTHY MINERALS.

Of gangue, or nonmetallic minerals, silica is the most abundant, but it rarely, if ever, occurs in the crystalline form of vein quartz. In sulphide ore bodies it is, like the metals, a replacement of the limestone, and the general term "jasperoid" has been given to designate all the varying forms of siliceous replacement. In the oxidized zone it may occur in granular form, retaining in great measure the limestone structure, or in lenslike sheets of chert, which often form the floor of an ore body, or, again, as the jasperlike matrix of the hard

[a] Zeitschr. für prakt. Geol., July, 1906, p. 217.

carbonate ores, and in the latter case seems to have been either transposed or added during oxidation. That there has been an actual addition of silica is not susceptible of direct proof, but the impression derived from a general inspection of the ore bodies is that on the whole the oxidized ores contain more silica than the sulphides.

The oxidized ores often appear very clayey, but except near the porphyry contacts, where there are clay bodies evidently resulting from the decomposition of porphyry, the percentage of alumina in the ores is very small, not amounting to over 1 or 2 per cent.

Barite and calcite are occasionally found in the oxidized ores, but form no considerable portion of them.

DISTRIBUTION OF ORE.

It would be rather inadvisable, even if it were possible, to give detailed descriptions of all the mine workings in this area, as they could hardly be made intelligible without detailed maps. An assembled map of the workings of the principal mines examined was made for the purposes of this study, and the most important general facts deduced from it, with regard to geological structure and distribution of ore, are represented on the accompanying map and sections. The outlines of the ore bodies are most indefinite in the mines themselves, owing to the very gradual and often imperceptible gradation from pay ore to slightly altered country rock, and it was possible to examine only a limited portion of the ore bodies that have actually been mined. For this reason, and in further consequence of the small scale of the map, it has been possible to indicate only in a very general and imperfect way the outlines and general distribution of the ore bodies. The object of the present chapter is to supplement these indications, as far as the data collected will permit, by a verbal description of the geological relations and distribution of the ore in the several mines or groups of mines. Such a description would necessarily be less intelligible to the general reader than to those actually occupied in exploiting the mines of the district. The general order will be followed of taking up first the ore bodies lying east of the fault, then those along the fault zone itself, and finally those in the region to the west of it, as far as it had been explored at the time of inspection. In accordance with local practice, ores that occur between the White and Gray porphyries will be called upper- or first-contact ores, those beneath the Gray porphyry second-contact ores, and those below the Parting quartzite third-contact ores.

AREA EAST OF THE FAULT ZONE.

CARBONATE HILL.

The sedimentary formations on Carbonate Hill have a fairly uniform dip to the east and south at angles of 15° to 20°, but there are

locally sharp bends or warps where, for a short distance, the strata have buckled down at much steeper angles, at some places approaching the vertical. There is one prominent intrusive sheet of Gray porphyry in the Blue limestone whose thickness, though varying from point to point, is prevailingly 50 feet or more. Its position is also variable, since, though generally found below the middle of the formation, it cuts across the beds at some places so as to approach their upper surface, and may split into two or more sheets. Narrow, dikelike bodies of Gray porphyry are also found occupying a more upright position, but many of these have proved to be offshoots or apophyses from the main sheet, and it is probable that all of them are of this character. A few of these dikelike bodies extend up to the White porphyry, either flattening out against its under surface or penetrating it a short distance beyond the contact.

Favorable positions for the accumulation of ore are near the under surfaces of the porphyry sheets, in the vicinity of the dikelike bodies and near the sharp bends of the strata, especially where the fold has passed into a small fault. The oxidizing action of the surface waters has reached rather unusual depths, in some places as much as 500 or 600 feet from the surface, probably because of the dip of the beds and the scanty covering of White porphyry above the limestone on its western face, so that with the exception of occasional residual masses of galena little or no sulphide ore has been mined on Carbonate Hill.

Ore has been developed most abundantly along the northern portion of the hill in the Crescent, Catalpa, Evening Star, Morning Star, Waterloo, and Henriette claims. At the time the original report was written there had been developed at the upper contact a large body of rich oxidized ore several hundred feet wide that had a general northeast trend along the four first-mentioned claims and reached its greatest development in the Evening Star, where it was up to 60 or even 80 feet thick. At the same time important bodies had already been developed at the second contact, or under the intrusive sheet of Gray porphyry. The main branch, outcropping near the Halfway House shaft, extended in a northeasterly direction into the hill, while the second or smaller branch, outcropping near the Forsaken branch and running northeast, joined the main shoot at about 300 feet from the outcrop. This ore body had a steeper dip than the upper contact for the reason that the Gray porphyry is crosscutting and has a slightly greater angle than the bedding planes. The manner of occurrence of the ore in these ore bodies is described in detail in the memoir of Mr. Ricketts,[a] who made a special study of them during the summer of 1882. The upper-contact ores were so rich, averaging perhaps 70 to 80 ounces of silver per ton, that even with the high cost of treatment then prevailing they yielded very high net returns, and the

[a] Ricketts, Louis D., The Ores of Leadville, Princeton, 1883.

Evening Star mine, with only 5 acres of ground, is said to have paid $1,400,000 in dividends to its stockholders in a few years. In the immediately succeeding years the ore bodies were followed vigorously northward and eastward, thus leading in later years to the development of the great ore bodies in the Maid and Wolftone mines. Most of the mines in this part of the hill were long ago abandoned, and it has been impossible to obtain such data as would permit an actual outlining of their ore bodies. It can only be said in a general way that a very great part of the ground in this portion of the hill has been found to be ore bearing, though it did not all pay to work at the time it was abandoned. The ore is by no means confined to the contact with the porphyry, but extends into the sedimentary beds along joint and fracture planes, which, in the oxidized zones, are with difficulty distinguishable.

A structural feature which has most important bearing on ore development is a strong downward bend in beds along an east-west line, passing just north of the Harker, Seneca, and Maid-Combination shafts. In places along this line it amounts only to a steepening of the southward dip of the beds from an average of 15° to 45°, 60°, or even 80°, while at other points it passes into an actual fault, of generally small displacement, and often distributed on several planes of movement. Along this line, especially on the upper and northern side of the bend, there has been an unusual ore concentration which can be traced, though not continuously, from the city of Leadville eastward across the northern ends of Carbonate and Iron hills nearly to Adelaide Park. In a vertical direction also mineralization has extended through an unusual depth, ore shoots having been found at successively lower horizons, though with no apparent connection between them, down to the Transition series of beds between the White limestone and Cambrian quartzite. In the lower horizon the silver content of these ores falls off very noticeably, even when the lead percentage is very high. For instance, 45 per cent lead ores have been found to carry only 2 to 3 ounces of silver to the ton.

The upper-contact bodies have been in great measure scored off from that part of the northern portion of the hill that comes within the boundaries of the present map, so that it can not be determined whether any connection has ever existed between them and those to the west of the fault zone.

Farther south, in the Shamrock, Carbonate, Little Giant, and Yankee Doodle grounds, a second series of upper-contact bodies have been worked out, which, though rather disconnected, have as a whole a general northeasterly trend. Of the later developments in this region very little information has been obtained. Apparently the area of upper-contact ores has not been very much increased. Various disconnected ore bodies have been opened within the mass of

the limestone alongside of or near the crosscutting dikelike bodies of Gray porphyry, but there is apparently no continuous second-contact ore body under the Gray porphyry sheet, though a few small pockets of ore have been found in places within the White limestone. From what has been learned of the distribution of ore under Carbonate Hill it would appear to have had a decided tendency to spread out and dissipate itself toward the south, as if the ore-bearing currents had originated at the northern end of the hill and had moved from there southwestward along bedding and contact planes, depositing their load slowly as they proceeded, at first in comparatively continuous shoots and then in smaller and more scattered bodies as the distance increased.

STRAY HORSE GULCH DEPRESSION.

Under the valley depression between Carbonate and Fryer hills, now occupied by the two Stray Horse gulches, a secondary or transverse fold is suggested by the fact that the beds to the south have a southeasterly and to the north a northeasterly dip. A little north of the limits of the present map there is an unusual development of crosscutting bodies, both of the White and Gray varieties of porphyry, which may have produced a doming up of the overlying beds, and thus this apparent anticlinal structure. Whatever the cause, the result has been that erosion has cut down to an abnormal depth and successively lower horizons have been laid bare beneath the Wash on the several benches produced by faulting, while the entire upper contact and a portion of the second contact have been carried away. The existence of such a second uplift was indicated on the original map, but an error was made in assuming an intervening syncline at the northwest base of Carbonate Hill around the Halfway House and Lower Henriette shafts. The reason for assuming this structure was that these shafts had apparently passed through White porphyry before reaching the ore, in which case the ore would have been upper contact, but in somewhat abnormal position. Subsequent developments, especially the discovery of the Niles and Pendery faults, have rendered it probable that this porphyry was simply a bleached and decomposed Gray porphyry in normal position above the second-contact ore body, as shown in Section IV (Pl. III).

The western continuation of this ore body has been mined in the Elk and Hussey grounds below the Niles fault, where it lies between the Parting quartzite and Gray porphyry, while the ore body found above the Parting quartzite in the drift running westward from the Niles-Augusta shaft is the probable continuation of the southern branch of this ore body that had been mined in the Forsaken and Lower Evening Star ground.

In the ground explored by the workings of the Elk and Hussey mines the general dip of the formations is to the southeast, there

being from 45 to 60 feet of Blue limestone, or ore which replaces it, between the Parting quartzite and the overlying Gray porphyry. The quartzite floor is somewhat corrugated by minor folds, but in general tends to flatten out to the northwest, while in the opposite directions the formations have a sharp downward bend a short distance to the southeast of the shafts, then flatten in a trough or basin, beyond which they bend up sharply against the Niles fault. This sharp downward bend is in a general line with that running east and west through the north end of Carbonate Hill. The ore, though not continuous, occupies a very considerable area, both in the basin and on the higher ground to the northwest. At many localities it replaces the entire thickness of limestone between the Gray porphyry and Parting quartzite. It was found to be rather richer than the average second-contact ore, its greater richness being probably due to the fact that, being so near the Wash, it has been more exposed to secondary enrichment. Numerous drill holes were sunk in various parts of this ground down into the White limestone in search of ore bodies at lower horizons, but without avail.

A drift across the Pendery fault, run westward from the Elk shaft at about 220 feet below the surface, has furnished data with regard to that fault that have so important a general bearing that they will be given in some detail. Toward the fault the Gray porphyry has been scored off and the limestone and ore lie immediately beneath the Wash. The drift on crossing the fault passes through limestone into brown clayey Lake bed material, which shows some sheeting parallel to the fault plane. Against the limestone, which forms the east wall, standing at an angle of 62°, there still rests a thin clay seam, in places black; at others a White porphyry clay containing fragments of chert, of such a nature that it could not have stood against an original cliff. It is thus proved that there must have been movement on the plane of this fault since the Lake bed material to the west of it was deposited. Further evidence is offered by the record of a drill hole, sunk from the same drift 160 feet west of the fault, which went through 78 feet of Lake bed material before reaching White porphyry in its normal position above the Blue limestone. On the east side of the fault there is 30 to 50 feet of rock above this drift before the Wash is reached, so that we have a sudden deepening of the rock surface to the west of the fault of over 100 feet, much, if not all, of which difference in level may be attributed to movement on the fault plane since the Lake beds were deposited.

North of the general line of the Hussey workings a number of isolated shafts, such as the Last Chip, Ypsilanti, Ida Nyce, Hope, etc., have found small ore bodies, presumably at the same general horizon as those of the Hussey, or second-contact bodies, but as the rather meager data obtained with regard to them were oral, and not

checked by personal examination underground, the structure represented on this portion of the map is of a lesser degree of accuracy than the average. The map shows, for instance, that the Niles fault gradually dies out to the north and passes into an anticlinal fold. This is simply the hypothesis that best fits the facts determined in the surrounding region, for the workings of the Jolly mine are the most northerly that are known to have cut this fault. Small faults have been noted in the Heytrosser and other mines, but their location is too uncertain to admit of their correlation with the Niles or the Carbonate fault.

Still farther north, in Little Stray Horse Gulch, the Turbot shaft found that the Gray porphyry sheet had been scored off, only the underlying formations being cut by it. The workings from this shaft developed a body of low-grade second-contact ore above the Parting quartzite, and discovered in the White limestone several small disconnected bodies of ore, running from 10 to 30 ounces of silver and 5 to 12 per cent of lead, but nothing that would be considered a continuous ore shoot.

Farther west than the Turbot, where the Parting quartzite has been scored off, considerable bodies of third-contact carbonate ore have been worked in the Walcott and Hibschle ground, just east of the Pendery fault, which averaged 10 to 150 ounces of silver to the ton and yielded several hundred thousand dollars during the first half of the decade 1890–1900. This ore was found in the lower part of the White limestone, extending in places down through the Transition beds into the upper part of the Lower or Cambrian quartzite, where it carried only 3 to 5 ounces of silver. The ore body was thoroughly oxidized, 10 to 25 feet thick, and in places extended in streaks higher up into the limestone, as if the original sulphides had been deposited along cracks or joints. The general trend of the ore in the Walcott ground was northeastward, the body extending from the Pendery fault near No. 2 shaft to the north of No. 1 shaft, and apparently sending off an irregular branch to the southwest into the Hibschle ground. The general strike of the beds in the Walcott ground is nearly east-west, and the dip is 18° to the south, but near the fault the beds bend down sharply to the west against the fault at 20° to 30°, striking somewhat west of north, parallel to the fault plane. The richness of the ore, unusual at this horizon, is doubtless due to its lying immediately under the Wash and being thus subject to enrichment by surface waters. As shown in Section IV (Pl. III), the No. 2 shaft was sunk in Wash and Lake beds just west of the fault, and the pronounced difference of level between the rock surface on either side of the fault affords additional evidence of movement on the fault plane since the deposition of the Lake beds, though as the depth of this surface west of the fault has not been determined, its actual amount remains uncertain.

FRYER HILL.

In the upper left-hand corner of the map is represented the southwest point of Fryer Hill. It will be recalled that this is about on the imaginary line that crosses the district from northwest to southeast, along which the White porphyry is found to split into two sheets, one of which cuts at a low angle across the Blue limestone toward the northeast, leaving a wedge-shaped tongue of that formation on either side of it, while the other sheet retains its normal position above the whole Blue limestone formation. Thus, on Fryer Hill, there is a sheet of White porphyry below as well as above the Blue limestone. The intrusive sheet of Gray porphyry is also crosscutting, and traverses the lower sheet of White porphyry, thus rendering the structure very complicated and difficult to follow. The workings from the new Clark shaft of the Chrysolite mine, which was sunk a short distance southwest of the Roberts shaft of the same mine, disclosed the fact that this crosscutting sheet of Gray porphyry, which outcrops under the Wash at the Colorado Chief No. 2 shaft, rises toward the northeast, so that at the Clark shaft it has traversed all the Blue limestone, and beyond that point it cuts up into the overlying White porphyry, bending upward at an even steeper angle until, before reaching the surface, it assumes the position of a vertical dike.

The enormously rich ore bodies which made Fryer Hill famous in the early days were replacements of split-off portions of the Blue limestone entirely inclosed in White porphyry. It is to be remarked that this hill lies just northeast of the northwest-southeast belt or zone along which the White porphyry sheet itself splits, one part cutting diagonally across the Blue limestone at a very low angle and leaving wedge-shaped slices of this rock both above and below it. Subsequent underground developments have confirmed the generalization made in the original report with regard to the existence of this crosscutting zone, though, as will be shown in the forthcoming general report, it is much more irregular and complicated than was represented on the original sections, which were based on a comparatively small number of observed facts. They have, moreover, disclosed the further significant fact that the wedge-shaped portions of the sedimentary series, more particularly of the Blue limestone but also, at some places, those of the Parting quartzite and White limestone, in the vicinity of the crosscutting White porphyry, have been favorable localities for the concentration of ore, and that where such ore bodies have been exposed by erosion so as to have been long subjected to the leaching action of surface waters, what remains of them has proved to be extraordinarily rich. It would naturally be expected, then, that the upper wedges, or those northeast of the crosscutting porphyry sheet, would be the richer, but if the lower or southwestern wedge happens to be faulted up to the vicinity of the surface and its covering of por-

phyry be removed, it may also become very rich. An instance of this was seen in the Mikado mine, which lies on a bench only 300 feet wide between the Iron and Mikado faults and from which rich ore, worth many millions of dollars, was extracted, while the western continuation of the same ore bodies to the west of the Mikado fault, opened by the R. A. M. and Greenback shafts, though of enormous extent both vertically and horizontally, being still covered by 600 to 800 feet of porphyry, are low in silver and are not only unoxidized, but have suffered comparatively little secondary enrichment.

Another rich body, but in oxidized ore and in the upper wedge, was that of the Small Hope Mining Company, in the Forest City and adjoining claims, where $6,000,000 worth of ore is said to have been taken out of 6 acres of ground. On Fryer Hill the Blue limestone is so completely replaced by oxidized ore that very little remains in its original condition. At some places the thickness of what was once limestone seems quite inadequate to represent the entire Blue limestone horizon, and it must be assumed either that some portions were floated higher up by the intruding porphyry and have been scored off, or else that portions were actually absorbed by the fused mass; but the general absence of any contact phenomena renders the latter assumption highly improbable. Those ore bodies that were under the lower or crosscutting porphyry were notably poorer in silver than the upper-contact ore, though carrying about as much lead. It has been impossible to learn what amount of exploration has been carried on in the White limestone, but whatever has been done has not apparently developed any large amount of ore. Still, by analogy with other parts of the district, it would be expected that some good bodies of ore should exist at this horizon, and they may yet be found.

Although very much warped, the formations in Fryer Hill have a general dip to the north and east; hence on the western end of the hill, where it slopes down to the terrace level, the White limestone and Lower quartzite come successively to the rock surface. The crosscutting sheet of White porphyry, which, on the southwest point of the hill that comes within the map, cuts down across the Blue limestone, farther north crosses the Parting quartzite also, and it would appear from the rather imperfect data obtained from certain shafts that it goes through the White limestone into the Lower quartzite farther north and west. It is possible, therefore, that somewhere in that direction it may come up through the granite, as it does at the mouth of South Evans Gulch.

Just east of the Pendery fault, at the west point of the hill and a short distance north of the area mapped, considerable bodies of manganiferous iron oxide have been mined through the shafts of the Allright No. 2 and the Fairview No. 4. These ores were found in the upper part of the Lower quartzite and were fully oxidized, but not

being rich enough in silver to treat for that metal were sold to eastern steel works as ferromanganese. They carried 18 to 25 per cent of manganese, 22 to 29 per cent of iron, and 9 to 18 per cent of silica.

AREA WEST OF THE FAULT ZONE.

POVERTY FLAT.

North of the limits of the map the Pendery fault has been traced along the west base of Fryer Hill and across Evans Gulch, in a few places having been actually cut by mine drifts, but for the most part being proved by the discrepancy in the strata exposed by shafts on either side.

On the gently sloping terrace popularly known as Poverty Flat, west of Fryer Hill and north of the moraine ridge, several shafts have been sunk to contact, such as the Hofer, Stumpf, Neptune, Jason, Seeley, and Delante Nos. 1 and 2, which, while not yet successful in finding any large ore bodies in the Blue limestone, to which their researches have thus far been confined, have furnished important geological data as to the lay of the sedimentary beds beneath the covering of porphyry. It thus appears that these beds descend in a gentle slope westward, taking here and there a sudden monoclinal plunge downward, but exhibiting no considerable displacement by faulting, and that at the same time they have a still more gentle dip southward. The overlying White porphyry sheet grows thinner to the west and north, while the Gray porphyry sheet, which lies above it, tends to increase in thickness in the same directions, but has been scored off the higher part of the ground near the Pendery fault. Farther north, toward Evans Gulch, an increasing thickness of shales and grits of the Weber horizon is found between the porphyry cover and the Blue limestone. Furthermore, a rather persistent bed of quartzose sandstone, about 10 feet thick, is found in the body of the limestone, and is liable to be mistaken for the Parting quartzite, both here and in other parts of the region. It is generally, however, a finer-grained quartz than the latter, is thinner, and occurs generally at a higher horizon, though its position is not uniform. It may be simply a siliceous replacement. The Blue limestone in this region, so far as it has been explored, includes no large intrusive sheet of Gray porphyry corresponding with that which is so closely associated with ore deposition in areas farther south and east.

CAPITOL HILL RIDGE.

Under the moraine ridge which connects Fryer with Capitol Hill, the first deep exploration of the Downtown area was made in 1880 by the sinking of the Bob Ingersoll drill hole to a depth of 500 feet. Though it found no ore, it furnished important geological information

by disclosing a thickness of 140 feet (at least) of White porphyry beneath the Wash and the Lake beds, from which it was reasoned that the Blue limestone must lie at a still greater depth. It has since been proved that had the drill gone 50 feet deeper it would have reached the limestone. More than ten years later a shaft was sunk a short distance southeast of the drill hole, and a drift run eastward at a depth of 460 feet (9,850 feet) [a] struck the Blue limestone within 100 feet of the shaft, rising at an angle of 50° toward the east. About 140 feet farther east the drift cut the Pendery fault, the great volume of water coming from which so enhanced the cost of mining that, after the ore above this level had been stoped out, work was abandoned for a number of years. When mining in other parts of the Downtown area had lowered the water level somewhat, mining was resumed here, and the ore was followed on the dip to the west of the shaft 128 feet deeper (9,722 feet). When the ore above this level had been extracted another period of rest ensued, until, in 1905, a drift run in from the Coronado shaft on the 660-foot level (9,645 feet) struck the ore body still farther west and nearly 60 feet deeper. This brief statement illustrates some of the vicissitudes to which mining in the Downtown district is subject. The ore in the Capitol, or Northern mine, as it has sometimes been called, is all upper-contact ore, none having yet been found beneath the intrusive sheet of Gray porphyry. It occurs at the immediate contact with the overlying White porphyry and extends to varying depths down into the body of the limestone. It is rather irregularly distributed, but in general arrangement has a tendency to form two shoots running in a northeasterly direction.

The geological structure in the Capitol ground is peculiar and significant. Within 10 feet of the Pendery fault the beds are dragged up into an almost perpendicular position by the movement of the fault, and the drift on the first level cuts through a wedge-shaped tongue of Gray porphyry dragged up from the intrusive sheet below before entering the granite which forms the foot wall of the fault. West of the fault the beds assume a westerly dip of 20° to 25°, and then, within 100 feet of the shaft, turn sharply down at 50°, the dip growing gradually less steep west of the shaft. In the steeper part broken and crushed material gives evidence of an actual downward slipping movement along this contact, which increases toward the south, as will be seen later, and finally passes into the Cloud City fold fault. At the Newell shaft, which was sunk a few hundred feet farther west, the contact is considerably above its lowest point in the Capitol ground, and a drift run westward found it still rising in that direction, while the Villa shaft, still farther west, found it immediately under the Wash at a still higher level (9,975 feet), thus proving con-

[a] Figures in parentheses in the text denote the elevation above sea level of the point referred to.

clusively the existence of a synclinal basin, as shown in Sections I, III, and IV (Pls. II and III).

The rise of the limestone at the Villa shaft seems to be local and abnormal, since the contact is over 100 feet lower at the Delante No. 1 shaft, a short distance farther north; for which reason it is assumed to be on the crest of the ridge, and that toward the west, as shown in the sections, the beds continue their normal westward dip for a considerable distance. Whether this is actually so and how far this dip may continue can be calculated only when shafts or drill holes shall be sunk to contact west of the line of Harrison avenue. In any event there is a very considerable area of possible ore-bearing ground in this vicinity which has thus far been practically untested.

CORONADO AND SIXTH STREET GROUND.

The sharp downward bend of the strata in the Capitol ground passes southeastward into a distinct fault which runs a short distance northwest of the Coronado shaft southwesterly past the Sixth Street shaft, and is undoubtedly the same fault which was struck by the Cloud City shaft, though it has not yet been continuously traced. What is apparently an eastern branch of the same fault is cut by the drift connecting the Coronado with the Capitol mine (9,645 feet), where it has a slight downthrow to the north. Whether it continues to connection with the Pendery fault or dies out before reaching it had not yet been determined.

Northwest of the main Cloud City fault, in Coronado ground, is a shallow syncline corresponding to that between the Capitol and Newell shafts, whose axis is approximately parallel to the fault, but whether this structure extends as far south as the Cloud City shaft remains yet to be proved. The upthrow of the fault is normal and to the southeast, but the amount of displacement of this, as of all fold faults, is extremely variable, since it becomes nil where it passes into the fold. In this case the throw increases to the southwest and the vertical separation is over 200 feet on the line of Section V (Pl. IV). As the beds bend sharply as they approach the fault from either side, the actual amount of throw, or movement on the fault plane, is somewhat uncertain.

Up to within very recent years the workings of the Coronado mine were confined to the upthrown or southeast side of the fault, but since the last consolidation of mines in this region work has been carried on at deeper levels, and second-contact ore beneath the Gray porphyry sheet has been found in the bottom of the syncline due west of the Coronado shaft. It is oxidized, but its extent and value are unknown.

In the earliest developments a large body of upper-contact ore is said to have been worked on the east of the shaft, but as these work-

ings have not been reopened since the "Flood," [a] they could not be examined. It probably corresponds to an upper-contact body that formerly overlay the Walcott body, whose western continuation would naturally have been found in the Coronado ground. A small body of upper-contact ore was found directly northeast of the Coronado shaft, but most of the ore worked later between the shaft and the fault was in scattered bodies. It occurs both above and below the intrusive Gray porphyry and within the mass of the limestone. The Gray porphyry is much decomposed, and is in places traversed by 1-inch seams of manganese oxide. Its horizon rises eastward. On the third level (9,702 feet), southeast of the shaft, a good deal of second-contact ore has been worked immediately above the Parting quartzite. This would appear to be a westward continuation of the Elk-Hussey ore shoot. At a still lower level a body of ore has been developed in White limestone, in close proximity to the Pendery fault, which is evidently a western continuation of the Walcott ore shoot.

Midway between the Coronado and Sixth Street shafts a very large ore body, averaging in places 80 feet in thickness, was found under the Gray porphyry associated with a sharp downward bend of the formation, which at some places passes into a cross fault with a southeast strike and an upthrow to the southwest. The under surface of the Gray porphyry is very irregular, tongues or offshoots protruding here and there into the ore beneath.

From the upper level (9,780 feet) of the Sixth Street shaft a first-contact ore shoot was worked which has a northeast trend. It lay above the Gray porphyry, and extended in places for 30 feet up into the limestone, but whether it reached the White porphyry contact is not known. Though less extensive and thinner than the second-contact body last mentioned, it was on the average rather richer in silver.

There is some uncertainty with regard to the geological structure of the ground west of the Sixth Street shafts (two shafts were sunk only 50 feet apart), which could not be worked out satisfactorily, owing to the inaccessibility of the upper and older drifts. There is some faulting between the two shafts, but the displacement does not seem to be sufficient for the Cloud City fault, and it may be only a parallel break. Again, a western drift on this upper level ran into

[a] About 1896 the labor unions obtained such complete control of the district that they not only stopped work in all the mines, but obliged the mine owners to draw their pumps, and the mines consequently filled up with water. This period is popularly spoken of as the "Flood." During the years that the drifts remained under water they gradually filled up with the lime sand, called by the miners "dolomite sand," that results from the disintegration of the Blue limestone. As the sand is extremely fine and preserves the original color of the limestone, its deposit in the drifts so closely simulates the bedding of the original limestone that, in reopening drifts cut through limestone, it is often difficult to distinguish this later deposit from the parent rock.

the Wash 200 feet west of the No. 1 shaft, which indicates a depression in the rock surface under the Lake beds—probably the old stream bed that forms the bottom of the Stray Horse depression.

MIDAS-PENROSE GROUND.

To the southeast of the ore bodies above described the ore horizon in the Blue limestone stands at a somewhat higher level, as disclosed by the drifts running from the Midas and Penrose shafts; but this is apparently due to a rise in the Gray porphyry sheet, since, as shown in Section XII (Pl. VII), the general tendency of the sedimentary beds is to descend gently to the southward. Around these shafts is the most extensive area of ore-bearing ground in the Downtown district. On the map most of the ore bodies have been designated second-contact ore because they lie beneath the Gray porphyry sheet; but Section XII (Pl. VII) shows that on that line the ore is all in the uppermost part of the Blue limestone, though it necessarily lies below the Gray porphyry sheet when that sheet has spread out immediately under the White porphyry, as is the case around the Penrose shaft and for a considerable distance to the north and east. The unusual concentration of ore in this vicinity is due doubtless to the irregular manner in which the Gray porphyry sheet has cut across the beds and sent off tongues and branching sheets at different horizons. The general structure and relations of the ore body are seen in Section V (Pl. IV), which runs southeastward through the Midas shaft, and in the parallel Section VI (Pl. IV), which cuts the Penrose shaft, as well as in the strike Section XII (Pl. VII).

Midas shaft.—Near the Midas shaft the Gray porphyry sheet rises to the White porphyry contact but dips gently down to the northwest and south, leaving a thin wedge of limestone between the two porphyries, which has been largely replaced by oxidized ore of good grade. The ore is streaked with clay resulting from the alteration of the underlying porphyry, of which, to a limited extent, it seems to be a replacement. To the north of the shaft it is 20 to 30 feet thick and about 150 feet wide, and appears to be in line with the great northeast ore shoot of the Penrose ground which underlies the Gray porphyry. Some ore is also found in the Midas ground, under the Gray porphyry, but its extent is not well known.

To the east of the shaft a broad zone of ore, up to 50 feet in thickness, runs north and south along the foot of the Pendery fault. This is second-contact ore underlying the Gray porphyry and may be considered an extension of the Elk-Hussey body. It is of rather better grade than the second-contact bodies in the Penrose, carrying on the average 12 ounces of silver, 0.01 to 0.02 ounce of gold, and 1½ per cent of lead, and has probably been enriched.

At the second level (9,750 feet) a long drift was run in a general southeasterly direction between the Bison and Gray Eagle shafts through Blue limestone and Gray porphyry, finding ore dipping steeply westward beyond the latter shaft. In the last 20 feet the drift is said to have been in granite, which apparently must have been beyond the Wildcat fault.

Penrose shaft.—At the Penrose shaft, and for a considerable distance north and south, the Gray porphyry sheet lies immediately under the White porphyry along the line of Section XII (Pl. VII), but it sends off several offshoots to lower horizons, so that in many parts of the mine there are two sheets, one above the other, and great complications of structure result, which can not be fully described or mapped. The ore has accumulated under both contacts, generally in rather shallow troughs, and is very apt to fill most of the spaces between two sheets when they are in close proximity.

In a general way most of the upper or White porphyry contact ore lay northeast of the shaft in a belt running northeast-southwest on either side of the Weldon fault. This, as has already been stated, is a fold fault with an upthrow to the southeast of not over 100 feet, along and above which are the workings of the Gray Eagle, Pocahontas, and Orion mines.

The ore is apt to be thickest on the upper bench, where bodies of black iron up to 80 feet thick have been found. Such bodies are of low grade in silver, except near the immediate contact, where rich lead and silver ores generally occur. The large body of black iron northwest of the Gray Eagle shaft, for instance, carried 16 to 18 per cent iron, 31 to 32 per cent manganese, and 8 to 11 per cent of silica, with 6 to 8 ounces of silver; while the carbonate ores had 43 ounces of silver, 12½ per cent of lead, 25 per cent of iron, 0.7 per cent of manganese, and 16 per cent of silica.

The most important shoot in the Downtown district lies, however, north of the Penrose shaft immediately under the Gray porphyry, and in its most typical development is over 50 feet deep and 150 feet wide, with a distinct northeast strike. This strike would carry it into the Midas ground, where, however, most of the ore lies above the Gray porphyry, which has come down in horizon, so as to leave considerable space for ore accumulation between it and the White porphyry. In the Penrose body it lies in trough-shaped channels under the Gray porphyry, the principal one trending northeast and smaller ones trending more to the eastward and tending to converge to the west. In spite of its oxidized condition, which renders structure lines obscure, it is possible to detect evidence of local folding and faulting, with axes in the direction of the shoots, which has rendered the ground favorable for the concentration and precipitation

of ore. There is the usual underlying bed or floor of black chert several feet in thickness, which is a siliceous replacement of the limestone. A peculiar white clay seam, containing small pebbles of porphyry, at many places divides the upper lead-bearing ore from the low-grade iron below. This may represent the outline of the original sulphide body. West of the shaft, on the same general southwest line, there is a large irregular body of low-grade iron (5 to 10 ounces of silver to the ton) 40 to 50 feet thick, which is unusually rich in manganese. At its southern end it is covered by 40 feet of Gray porphyry, which immediately underlies the White porphyry. At a point midway between this body and the shaft an isolated, dikelike body of Gray porphyry was observed, which has not yet been connected with any other porphyry mass. It stands in a vertical position, is 35 feet thick, and has a flow breccia at its contact with the limestone.

Bison shaft.—Due east from the Pendery the Bison shaft was sunk in an area of extremely complicated structure, where the ground is so sliced up by faults and branching sheets of Gray porphyry that it is very difficult either to work or to interpret. The abundant faulting has, however, been very favorable for secondary enrichment, so that unusually rich ores have rewarded the difficult labors of the miner. As for the structural problem, the solution represented on Section II (Pl. II) and Section V (Pl. IV), each of which passes near the Bison shaft, is believed to be correct in its broader features, though there are many complications in structure that can not be represented on a map of the present scale, and the ground could not be thoroughly studied, for the reason that the mine has been worked intermittently by different persons and the records not always preserved. In this ground is the point of an eastward bend in the Pendery fault, and across this bend a second fault constitutes the chord of the arc made by the Pendery fault. This fault, which is cut by the Bison shaft just above its first level, is normal, and is called the Bison fault. A little east of the shaft on this level is another small fault, with reverse throw, which has been interpreted as cutting off a wedge-shaped mass that has dropped down, while at the end of the drift is the main Pendery fault, which brings the Parting quartzite up against the Blue limestone. East of this fault, and about 80 feet higher, a west drift from the Niles-Augusta shaft struck a good body of second contact ore above the Parting quartzite. In the Bison workings to the east of the shaft there is a duplication of the Gray porphyry, which is supposed to result from its sending off an offshoot, as represented in Section II (Pl. II).

In the later workings of the mine, drifts run westward from lower levels cut the Bison fault and found large and valuable ore bodies beyond it, mainly in the limestone and under the White porphyry, but it is said that a second-contact body corresponding to the Niles-Augusta

has recently been found. It will be observed that the line of second-contact ore bodies has been opened intermittently in a direction due east from the Penrose shaft, and if followed farther eastward in this direction across the north end of Carbonate Hill, tends to correspond approximately with the sharp bending down of the strata to the southward, already noted in that region.

About 200 feet south of the Penrose shaft, under the Lazy Bill shaft, is an ore shoot which has the fissure form, like those occupied by the ore bodies on South Iron Hill, and is so far the only known example of this type of body in the present area. It lies under the Gray porphyry and has evidently been formed from solutions coursing along a fissure striking northeastward, with northwest dip, and eating out into the limestone on either side. Along this fissure were some large chambers of rich ore carrying 100 to 200 ounces of silver and 20 per cent of lead. Both strike and dip are irregular and wavy. As shown in the drift below (9,700 feet), the ore has pinched out, but the crack or fissure in the limestone can still be detected and forms what the miner calls a watercourse or channel along which surface waters still seep down.

STARR AND CLOUD CITY MINES.

Neither the Starr nor the Cloud City mine had produced much ore at the time of examination, and the ore bodies that had been worked in the former ground are no longer accessible, so that not much can be said about actual ore development. As the geological structure may have some bearing on future development, and its description needs graphic illustration, the section in fig. 1 has been constructed from such data as could be obtained. It runs southeast through the Cloud City and Starr shafts and a little south of the Alice shaft, following the dip of the beds, which thus appears steeper than in many of the map sections, whose lines are not strictly at right angles to the strike of the beds. The principal ore bodies worked in the Starr ground have been near the Weldon fault, east of the shaft and immediately under the White porphyry. They were reached by numerous raises from the first level and evidently belong to the same general belt worked in the Penrose and Gray Eagle mines, to the northeast, and the Weldon, to the southwest.

As the formations rise to the northwest, there is a slight local fault near the place where the Gray porphyry sheet, whose thickness varies from 30 to 50 feet, crosses the second level (9,735 feet). Some ore has been developed to the west of the Starr shaft under the Gray porphyry sheet, but the country rocks in this part of the ground have been so softened and decomposed by the seepage of surface waters, indicating a probable close proximity to the rock surface, that mining is difficult and expensive, and the workings soon become inacces-

sible to the visitor. The drift running from the Starr to the bottom of the Alice shaft (9,750 feet) in the last few feet passes through a peculiar broken material (shown also at the top of several upraises) that has apparently been subjected to such differential movement within its mass as would take place in landslide material. The structure lines are obliterated, and it is full of broken angular blocks very much resembling decomposed Gray porphyry.

The bottom of the Alice shaft is in a bed of quartz sand, such as forms a very persistent stratum, 10 to 12 feet thick, in the lower part of the Blue limestone throughout the Penrose ground. The revelations made by the Cloud City shaft, which passed through similar broken material immediately under the Lake beds, suggest that the

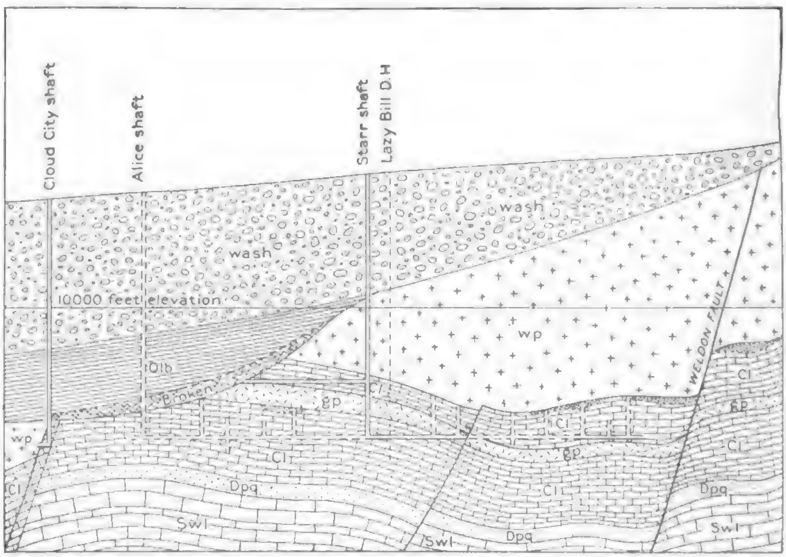

FIG. 1.—Section through Cloud City and Starr shafts. (For meaning of symbols see Pl. I.)

rock surface lies at an angle so steep that there has been an actual slipping downhill of a considerable thickness of moistened and rotted rock on what happened to be an exceptionally steep slope of the surface of the rock beneath the Lake beds.

The double line given on the section under the Lake beds indicates the possible thickness of this broken material, though it is impossible to determine any well-defined boundary lines for it, since it grades off insensibly into the formations above and below. The abnormal steepening of the rock surface brings the upper part of the Blue limestone and the included Gray porphyry to outcrop along this line, a phenomenon that could not be observed elsewhere owing to the absence of drifts, so that the crescent-shaped form of the outcrop indicated on the surface map is for the most part theoretical. It is

based on the assumption that there was a gullylike depression in the rock surface beneath the Lake beds in this region which thus far has been cut only in the north drift from the Cloud City shaft. There is, however, a very considerable area of unexplored ground between the Alice, Sixth Street, and Penrose shafts, in which it may yet be found. It is possible that it may have some connection with the depression already noted west of the Sixth Street shaft.

At the Cloud City shaft the fault movement is distributed on two planes running a little east of north and about 50 feet apart, while a wedge-shaped mass has been let down to the west of the western plane on which the displacement is reversed. This renders the structure at the very bottom of the shaft rather difficult to interpret, especially as the drifts on the first level (9,710 feet) cut these planes diagonally. White porphyry is found in place beyond all the faults, however, and in it the old stream bed, already mentioned, has been cut through by the north drift, in which it is seen to be about 70 feet wide and filled with bowlder wash. The Blue limestone contact is cut by this drift 75 feet from the shaft and also in several winzes sunk to the north and west, which indicate a dip of 15° or 20° in this direction. It is very possible, therefore, that the synclinal structure found in the Capitol ground may be repeated here, though probably in less pronounced form. It is assumed that the vertical separation produced by the movement of this fault is from 150 to 200 feet; hence to properly prospect the ground to the north and west the shaft should be sunk 200 feet deeper. If the Gray porphyry is found to extend in that direction, there is very good reason for assuming that valuable ore bodies may be found.

WELDON GROUND.

The Weldon ground, although it includes only a single claim, 300 feet wide, has produced a remarkably large amount of rich upper-contact ore, carrying several hundred ounces of silver per ton. The main production has come from the lower (No. 2) shaft, which was sunk to the bench below the Weldon fault. The No. 1 shaft, opened earlier but long ago abandoned, was sunk in the midst of the fault zone, and cut the Pendery fault a little below its second-level station (10,068 feet). It disclosed a complicated structure, the general features of which are shown in Section VII (Pl. V), which, however, passes to the north of the Weldon No. 2 shaft, whose workings are shown on Section VIII (Pl. V).

No. 1 shaft.—At the No. 1 shaft several small ore bodies were found along the upper contact on the steeply sloping bench east of the Pendery fault, both north of the shaft, toward the Pocahontas, and east of it, toward the Pendery and St. Mary's shafts, where it lies in troughlike depressions called "swags" by the miners. A drift

run westward from the bottom of the shaft (9,910 feet) cut the Pendery fault, finding beyond it a body of Gray porphyry which was at first supposed to be a dike, but is really an intrusive sheet of Gray porphyry turned up steeply against the fault, the upward bend having been so sharp as to produce some slipping along its upper contact. Some upper-contact ore was found on the bench between the Pendery and Weldon faults, but on neither side of the Pendery fault in this region does the ground appear to have been thoroughly explored for second-contact ore.

No. 2 shaft.—The beds on the bench reached by the Weldon No. 2 shaft are compressed into a series of gentle wavelike folds. To the east of the shaft they descend 25 feet in a hundred, the contact coming down to the drift level (9,780 feet) and then rising at first gently and near the Weldon fault very steeply, so that at the fault the contact is 90 feet above the level. At the same time, the beds dip slightly south, so that the ore, which is 20 feet thick above the level on the north side of the claim, is entirely below it on the south. About 40 feet south of the shaft the White porphyry contact comes down into the level with a southwest dip, showing its characteristic chert fragments and being somewhat sheeted as the result of movement along the plane of contact. On the Weldon fault considerable ore was found in the upper 6 feet, which had been dragged in from the adjoining ore bodies.

To the west of the shaft the beds are still more crumpled and in some places slightly faulted. The Gray porphyry is very irregular and very difficult to trace. Farther west it appears to split, one branch rising above the first level (9,780 feet), as it does in the Starr ground; the other descending and possibly connecting with that in the Bohn ground, which stands at a much lower level—9,600 to 9,669 feet.

BOHN MINE.

There is a good deal of uncertainty about the structure of the ground between the Starr, Weldon No. 2, and Bohn shafts, the rocks being very soft and decomposed and the old drifts largely inaccessible. The intrusive sheet of Gray porphyry is about 60 to 70 feet thick and stands at a lower level relative to the White porphyry contact than at either the Starr or Weldon shafts. In the Bon Air ground, to the south, it retains the same thickness and descends at the same dip as the limestone, or possibly a little steeper dip. To the west in the Bohn ground this sheet rises in horizon, not uniformly but in gentle rolls, and thins out to 35 and then to 25 feet in thickness. At the Bohn shaft it sends off a vertical dikelike offshoot, 25 feet thick, which cuts the first level of the Bohn mine (9,778 feet) just south of the shaft. The ore in the Bohn ground has been mostly taken from the upper contact to the south and west of the shaft, but on the second

level (9,718 feet) some small pockets of ore have been mined under the Gray porphyry. The formations in general descend to the south and southwestward, and at 240 feet west of the shaft a zone of porphyry and limestone breccia running north-south may, it is thought, represent the Cloud City fault. It is not, however, seen in the upper level, nor does there seem to be any considerable displacement of the beds on either side. As disclosed in the Home Extension shaft, still farther west, where the contact stands at 9,680 feet, the drop might be accounted for by the slope of 22°. It is probable, however, that there is a downward displacement of about 50 feet.

BON AIR MINE.

At the time of the examination this mine was not actively worked and the ore stopes were not visited. They lie mostly above a single level (9,669 feet), by which the mine was then opened, and at the White porphyry contact. This contact has an average slope of 10° to the south, and at one point comes down in a synclinal roll to the floor of the level. The ore bodies are said to be from 10 to 25 feet in thickness and of rather low grade, averaging about 8 ounces of silver to the ton. They are generally underlain by chert in varying thickness up to 10 feet. Three drill holes have been sunk from this level down to the Parting quartzite without finding ore, but this seems to be insufficient ground for assuming that it does not exist there. To the east, toward the P. O. S. mine, the beds rise at an angle which steepens as this ground is approached, the more rapid rise being probably influenced by the general uplift along the fault zone. As the P. O. S. mine was being actively worked at the time visited and was studied in detail by Mr. Irving, it will be described rather fully, since it presents a structure typical of the fault zone.

P. O. S. MINE.

The P. O. S. mine is opened by a shaft situated on the western slope of Carbonate Hill, 350 feet southwest of the Portland, 600 feet northwest of the Can shaft, and 640 feet east of the Bon Air shafts. It reaches the White porphyry–limestone contact at a depth of 507 feet (9,791 feet) and has two levels at elevations of 9,771 and 9,762 feet, the drifts of the upper level lying to the east and those on the lower level to the west of the shaft. The ore thus far extracted has been found at this contact, which has a generally southwesterly dip at an average angle of 25° to 30°. Locally, however, there are sharp downward bends in the strata along which ore is apt to accumulate, as shown in fig. 4, section BB.

At the contact the White porphyry is decomposed and altered for a distance of 6 feet or more to a soft white clay, which is sheeted or foliated parallel to the bedding of the limestone, and the clay contains fragments of black chert which have been sheared out of the

Blue limestone, where it normally belongs, thus affording conclusive evidence of movement on this plane. The clay is much stained by manganese oxide, and dendrites of manganese extend up into the porphyry above the altered zone.

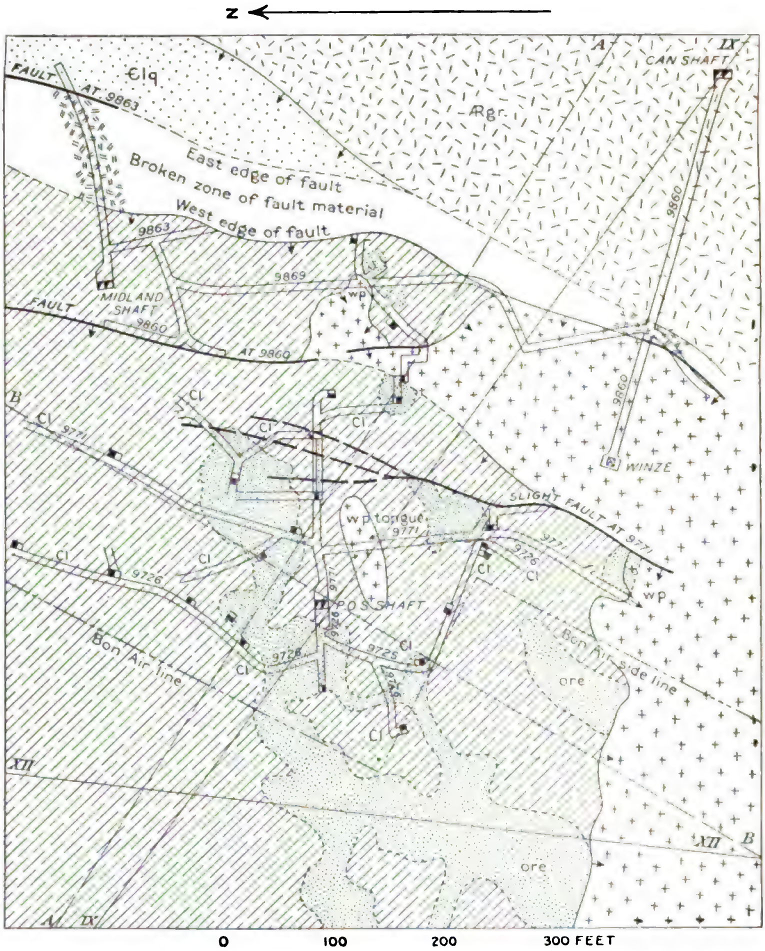

FIG. 2.—Plan showing the workings of the P. O. S., Midland, and Can mines at the working levels and the rocks exposed by the drifts on those levels, the elevation of the latter above sea level being indicated by figures within the drifts. The outlines of the ore bodies are projected onto this plan. Figs. 3 and 4 are partial sections along the lines *AA* and *BB*, which run respectively southeast and southwest across the area of the plan. Symbols: Ʀgr=granite; Ꞓlq=Cambrian quartzite; Cl=Blue limestone; Wp=White porphyry.

In the southern portion of the mine the dip of the formation brings the porphyry down across and below the level of the upper drifts, as shown on the map.

Faults.—The Pendery fault is represented by a zone of broken rock, mostly quartzite (*bq* on fig. 3), which is 25 feet wide in the Can ground and reaches 100 feet in the Midland ground. The vertical separation

of this fault, as shown on the general section, IX (Pl. VI), is about 850 feet for a throw of about 1,100 feet. The east drift from the Midland shaft, after passing through about 100 feet of fault material, mostly broken quartzite, penetrated solid Cambrian quartzite beyond. It is

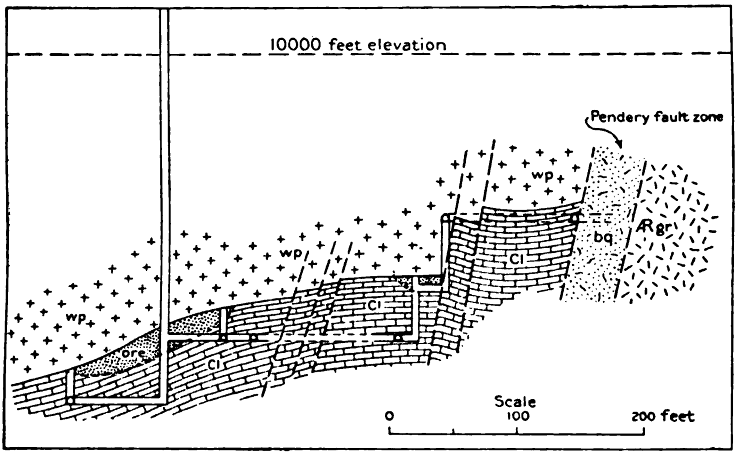

FIG. 3.—Workings of P. O. S. mine. (For meaning of symbols see fig. 2.)

assumed here that this lies between the Pendery and the Carbonate faults, the latter having bent westward to join the Pendery just north of the Can shaft. This is, however, only an assumption, as this part of the ground has not yet been explored.

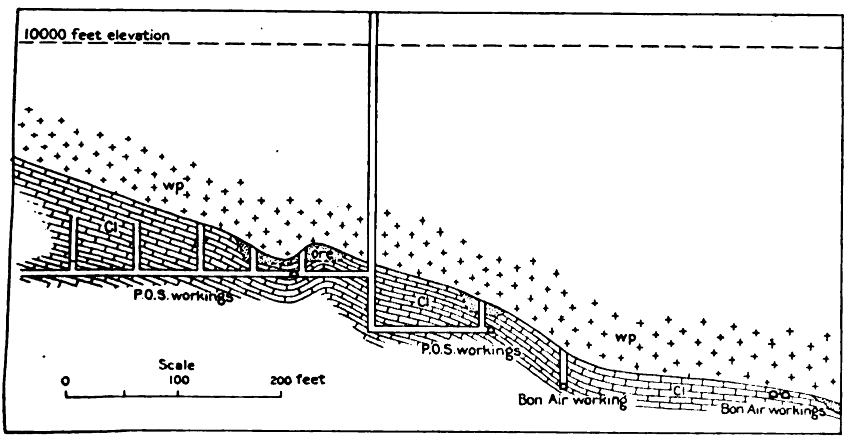

FIG. 4.—Workings of P. O. S. mine. (For meaning of symbols see fig. 2.)

Another fault runs parallel to the Pendery, about 200 feet to the west, which is well exposed in various upraises. It has a throw of not over 65 feet, but, owing to its limited lateral extent, has not been represented on the general map. A number of still smaller faults run

for short distances parallel to this, which apparently converge to the south and finally join it, as shown on the map and in figs. 3 and 4. They illustrate the complication of smaller faults which are apt to accompany the larger ones and render it difficult to work out all the details of the underground structure.

Ore.—The ore of the P. O. S. mine is an altered manganiferous iron, some of it carrying as high as 200 to 300 ounces of silver. The silver is often visible in beautiful greenish crystals of horn silver lining cavities in the ore. Cerussite is found irregularly disseminated through the siliceous "liver-colored" rock, constituting a hard carbonate ore. It occurs normally in a mass of black iron, but immediately below the porphyry, as shown in the diagrammatic section below (fig. 5). The ore in the P. O. S. occurs in three distinct shoots, only one of which had been sufficiently explored at the time of visit to disclose fully its geological relations. This lies on the north side of the shaft, but does not extend up to the fault that separates the P. O. S. from the Midland workings. It lies close up against the White porphyry, from which it is rarely separated by any unreplaced limestone. It is extremely irregular in outline and varies from 20 to 30 feet in thickness.

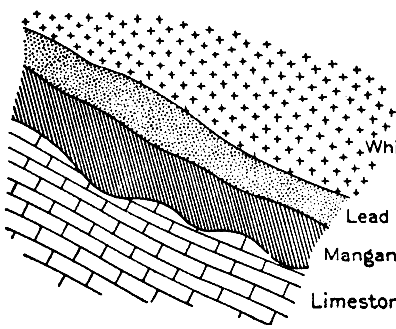

FIG. 5.—Diagrammatic section of ore body, P. O. S. mine. Shows the occurrence of the carbonate ore next to the White porphyry.

To the west of the shaft on the lower level is the northeastern continuation of an ore shoot which extends into the Bon Air ground. Other ore bodies on the upper level and south of the shaft had just been opened at time of visit and were about 25 feet in thickness. The ore is cut off on the east by a smooth limestone wall, dipping 65° west—the foot wall of a fault that can not have much throw, since the bottom of the Can winze on the level above and farther east is still in White porphyry.

Little or no ore was found in the Midland mine, whose workings are in ground so faulted and broken as to make successful mining rather difficult. In the Can mine, whose workings are largely in granite or White porphyry, no ore has been found.

SOUTHERN EDGE OF AREA.

So far as can be learned, no large amount of ore has been mined south of the P. O. S. ground. Considerable underground exploration has been done from the May Queen and O'Donovan Rossa shafts, but they were evidently unsuccessful in finding ore and have long been abandoned.

The California tunnel was visited in 1880 and found to run 700 feet into the hill, of which the first 585 feet went through White porphyry to a fault, which is evidently the Pendery fault. The tunnel passed beyond it into a limestone, supposed to be the Blue limestone, which bends downward against the fault plane with a western dip of 40°, but farther in shows a normal southeastern dip.

An east drift from the California Gulch shaft, at the southern edge of the map, also cuts the Pendery fault, whose position on the surface has been calculated with reference to the measurements given by the working maps of this mine, the mine itself being closed down. The shaft passed through the intrusive Gray porphyry and found a considerable thickness of mineralized matter beneath this, as well as beneath the White porphyry.

The tracing of the Pendery fault thus far may therefore be regarded as rather accurate, but with regard to the southern continuation of the Carbonate fault there is less certainty. It has not been actually cut underground south of the Ætna mine, and its curving connection with the Pendery fault, represented on the map, is a theoretical assumption deduced from the apparent converging direction of the two faults and the failure to find any well-defined duplication of beds on the outcrops on the steep southwest slope of Carbonate Hill. The latter is rather negative evidence, as the covering of slide rock is so deep that there are very few actual rock outcrops, and the prospect holes that have reached rock in place are very scattered and difficult of access. On the other hand, drifts running eastward from the Toledo Avenue shaft cut a fault that crosses California Gulch in a northerly direction, and a wedge-shaped fault was found 375 feet from the mouth of the Prospect incline, halfway between that shaft and the Carbonate incline. Moreover, according to the outlines indicated on the map, the limestone cut beyond the fault by the California tunnel must be the lowest part of the White limestone instead of the Blue limestone, as was supposed at the time of visit in 1880. Whether the Carbonate fault is correctly represented on the map or continues southward in a more easterly position, faults of minor throw undoubtedly cross California Gulch east of the Pendery fault, as is shown by discrepancies in the beds, and one of them passes through the Revenue shaft on the flat south of the gulch. The structure shown on Section II (Pl. II), which has been continued to the west of the area mapped in order to incorporate the data given

as to rocks passed through by the Valentine and Maple Street shafts, shows that the descent westward of the Blue limestone is not so steep but that it can be accounted for by a westward dip in the beds which is not greater than is elsewhere observed in the Downtown area, though a fault of small throw is said to have been proved by underground workings west of the A. V. shaft and a little east of the Valentine shaft.

Prospecting in this southern area must always be attended by considerable risk, as an indispensable preliminary is the sinking through 400 to 700 feet of necessarily barren material before the horizon of possible ore can be reached, and when reached there are as yet no well-defined lines of probable mineralization to guide the miner in his exploration. On the other hand, the highly altered condition of the rocks passed through by such shafts as the A. V., which have been sunk in this area, indicate a probable extension of the area of mineralization beyond that already explored underground.

GENESIS OF ORES.

MISCONCEPTION OF ORIGINAL VIEWS.

The explanations given in the original reports on the Leadville district of the origin and formation of the ores in limestone have been in many respects very generally misconstrued in subsequent publications. In some of these the writer is assumed to have stated that the ores were brought in by waters descending directly from the surface; in others, that the metallic contents of these waters were derived from the overlying White porphyry, neither of which views he actually held. It would seem that the authors of these publications must have formed their opinion from reading only the preliminary statement, published immediately after the close of field work in 1882, rather than from the more complete explanation given later in the Leadville monograph. In the former[a] it was briefly stated with regard to the origin of the deposits:

1. That they have been derived from aqueous solutions.
2. That these solutions came from above.
3. That they derived their metallic contents from the neighboring eruptive rocks.

In the final report[b] this statement was made more explicit, as follows:

> With regard to the *immediate* source from which the minerals forming these deposits were derived, the following conclusions have been arrived at:
>
> 1. That they came from above.
> 2. That they were derived, mainly, from the neighboring eruptive rocks.

[a] Second Ann. Rept. U. S. Geol. Survey, 1882, p. 234.
[b] Mon. U. S. Geol. Survey, vol. 12, 1886, p. 379.

By these statements it is not intended to deny the possibility that the material may originally have come from great depths, nor to maintain that they were necessarily derived entirely from eruptive rocks at present immediately in contact with the deposits.

The facts and reasons on which these conclusions are based will be given in the following chapters.

At the time the preliminary report was in preparation capitalists were being urged by J. Alden Smith, State geologist, to sink deep shafts immediately down to the Archean, on the theory that, since ore-bearing solutions came from below, the Leadville ores must necessarily have ascended through fissures in the underlying granitic rocks, and the ore bodies found there, being nearer to the source, would be more valuable than those found in the limestone, his belief being that "these fissures and deposits will be extensively and profitably worked for centuries after the contact deposits now operated are exhausted." [a]

In the light of the geological investigations he had made, this seemed to the writer a mistaken idea, which, if followed, would result in pecuniary loss and might retard the development of the district; hence he made his statement strong, and, as results have since proved, rather too unqualified.

Geological studies of ore deposits up to that time had been, mainly, of veins that follow nearly vertical fissures in the rocks, of which the most natural explanation is that they are formed by ascending solutions; and in ordinary mine reports, for which, as a rule, but little study of the general geology of the district was deemed necessary, the rather perfunctory statement was generally made that the vein materials "came from below," without any very definite understanding on the part of the writer of what these words implied.

It was, moreover, generally assumed that all waters circulating within the crust of the earth came originally from the surface, descending under the influence of gravity and ascending again under the influence of heat—either the normal increment of heat within the crust, or that due to proximity with some cooling igneous mass. The modern idea that cooling igneous masses have given off enough occluded water to furnish a continuous underground circulation was then, and for many years afterwards, not considered tenable.

In undertaking the study of the Leadville mines, the writer proposed to take a new departure in making, as a preliminary, a thorough study of the geological structure, not only of the immediate vicinity of the mines but of the whole mountain region within a radius of about 10 miles around, and to base his attempt to explain the manner of formation of the ore deposits on the geological data thus obtained,

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[a] Rept. on mineral and other resources of Colorado for 1881 and 1882, p. 64.

quite independently of whether the resulting explanation accorded with current theories or not. As it was his first study of any important group of ore deposits, he did not feel competent to go into abstract questions about their origin, much less to present a general theory of ore deposits, as some seem to have assumed he did; hence, in speculating as to the source of the metals, he thought it wiser, as the important object was to furnish a guide to the miner in his search for ore bodies (as stated explicitly in the text, Monograph 12, p. 572), "to leave out of consideration altogether the ultimate and purely speculative source and to confine the investigation to the more immediate source, about which it was possible to obtain some actual and demonstrable evidence." Then, after stating that the commonly received explanation for vein deposits is that they have been formed by directly ascending heated solutions, he said,[a] "In the case of the Leadville deposits, the inadequacy and even falsity of this explanation, *except as applied to the ultimate source from which the metals may have been derived*, is readily apparent." He then proceeded to give the reasons for this statement by showing that the form of the ore bodies was such as to lead to the conclusion that the ore-bearing bodies entered the limestone from its contact with the porphyry sheets. These contacts being the main channels of circulation and mainly at the upper surface of the limestones, "the few approximately vertical bodies [of ore] that have come under observation afford no evidence that their walls form part of a channel through which the ore currents came up from below;"[b] hence, he concluded, "the above considerations seem sufficiently conclusive evidence against adopting upward currents as the direct source of the ore deposits of Leadville."

In further argument against the necessity of resorting to the unknown depths to find the source of the metals, the author proceeded to give the result of chemical tests of the country rocks, especially those of igneous origin, which showed that small amounts of vein material were found in most of the latter and that most of the varieties of porphyry, except the White porphyry, contained appreciable amounts of silver. Then, without attempting to decide which particular variety of porphyry the metals came from (which he explicitly stated was "too difficult because of the amount that had been removed by erosion since ore deposition"), he said: "The foregoing reasons seem to favor the probability that the ores may have been derived, in part at least, from one or more of the bodies of porphyry which occur in the region.[c] * * *"

While the intimate genetic connection between the ores and porphyry was established, as he conceived, with reasonable certainty,

[a] Loc. cit., p. 572. [b] Loc. cit., p. 573. [c] Loc. cit., p. 584.

he admitted that there was still some doubt about the ultimate source of the metals, remarking:[a]

It is possible that in future years, when mine workings shall have been extended over areas where the ore horizon exists at considerable depths below the surface and other eruptive channels have been found and critically examined, evidence may be obtained that ore solutions have ascended along these channels from below.

The idea that was in his mind in saying this was that inasmuch as the Gray porphyry within the mineral area is a distinctly later eruptive than the White porphyry, if the channels were found through which this porphyry had reached the Blue limestone horizon these might prove to be also the channels through which the ore-bearing solutions had reached that horizon.

CRITICISMS.

In the time that has elapsed since the Leadville report was written some of the conclusions have been severely criticised by prominent geologists, notably the genetic connection of ore deposition with igneous eruption and the metasomatic replacement of limestone by ore, but practically all of these conclusions may now be regarded as universally admitted by economic geologists, with the exception of the determination of source of the metals. With regard to this, it may be said that in treatises on ore deposits written within that time the general opinion seems to be that the writer wrongly conceived the ores to have been brought in by descending waters, but that mining engineers, who had become more familiar with the deposits by later and more continuous underground observation, had proved them to have been brought up from below by hot ascending solutions.

Having already endeavored to show in what respect the author's statements were misconstrued, it may be well to see how far these statements are justified by a careful consideration of the articles on which they were based.

The mining engineers to whose writings references had been made were Messrs. F. T. Freeland,[b] Charles M. Rolker,[c] and A. A. Blow.[d] Of these, Mr. Freeland did not discuss at all the source or origin of the metals. Mr. Rolker, confining himself to the direct source, objected chiefly to the assumed statement of the writer that the ore-bearing solutions descended directly and exclusively from the overlying White porphyry, inasmuch as his own observations show that on Fryer Hill, where he had been in charge of an important mine, the ore bodies do not occur exclusively or predominatingly on the upper contact of limestone with porphyry, and that they appeared

a Loc. cit., p. 584.

b Sulphide deposits of South Iron Hill: Trans. Am. Inst. Min. Eng., 1885, vol. 14, 1886, pp. 181-189.

c The Leadville ore deposits: Ibid., 1885, vol. 14, 1886, pp. 273-292.

d The geology and ore deposits of Iron Hill: Ibid., 1889, vol. 18, 1890, pp. 145-181.

to have a closer genetic connection with the Gray than with the White porphyry. His general statement with regard to the deposits of the district, however, is as follows:[a]

> They are found mainly as contact deposits between the Carboniferous limestone and the overlying felsite, with additional or incidental ore accumulations in the limestone in irregular cavities, directly or indirectly connected with the plane of contact by irregular and often minute conduits, which a careful search reveals.

This statement, as far as it goes, is a confirmation of that of the writer.

In a subsequent article in the same periodical[b] the writer has pointed out how far the apparent discrepancy of their views arose from a misconstruction, on the part of Mr. Rolker, either of his statements or of the facts.

Mr. Blow's article, based as it was on nine years' continuous observation of the practical extraction of ore in a part of the region where the ore bodies have been deposited to a considerable extent along vertical fractures as well as on the more or less horizontal contacts and bedding planes in the limestone, constituted an invaluable contribution to the geological history of Leadville ore deposits, and his conclusions from actually observed facts, such as the origin of manganese in the oxidized ores, and of secondary enrichment, especially of zinc in the upper part of the sulphide bodies, showed remarkable acumen in observation and reasoning. The more theoretical part of his article, relating to what the writer would have called the ultimate source of the metals, is, however, less satisfactory, because, while professedly intended as a refutation of the writer's views, it starts with a misconception of those views, and also because it brings no observed facts to support those which he proposes as a substitute for them.

The misconception consists, first, in his failing to appreciate the fact that the writer was speaking only of the immediate source and declined to discuss the ultimate and theoretical source, and, second, in his mistaken assumption that the writer stated that the metals were derived from the White porphyry. The main part of his argument is devoted to the refutation of this latter mistaken assumption, and is purely negative; but, when he comes to his positive assertions, he simply gives as the alternative source the word "below," the use of which the writer had deprecated because of its indefiniteness; and as to the manner in which the solutions reached the present locus of the ore bodies, or what the writer would have called the immediate source, he says:[c]

> 2. That such ascending solutions more readily penetrated the limestone along the planes of contact of the igneous and sedimentary formations, and through zones of least

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[a] Loc. cit., p. 282.

[b] Genesis of certain ore deposits: Trans. Am. Inst. Min. Eng., 1886, vol. 15, p. 125.

[c] Trans. Am. Inst. Min. Eng., vol. 18, 1890, p. 174.

resistance in the latter previously marked out by the intrusion of the porphyries, and gradually replaced the limestone with their metalliferous contents in the form of sulphides.

The writer, in seeking for reasons for the location of the majority of the ore bodies in the Blue limestone, states:[a]

The great intrusive sheets of porphyry are found to follow it most persistently, mainly along the upper surface, less frequently along its under surface, and also cutting transversely across it. These intrusive bodies are also found at other horizons, it is true, but at none so persistently and so uniformly as at this. Thus both ascending and descending currents would readily reach these beds, the latter trickling through the uniformly permeable eruptive rock, the former following up the walls of the channels, through which it was erupted.

Thus, taking into consideration the greater development of ore bodies and intrusive sheets of Gray porphyry which had been shown to exist at the time Mr. Blow wrote, the difference in view between him and the writer is not essential, for he does not bring any facts to bear against the latter's third reason for declining to accept upward currents as the direct source of the ore,[b] i. e., "the noticeable absence, in the region of greatest ore development, of channels extending downward, through which the ascending solutions might have come." Indeed, in his descriptions he speaks of the ores as going downward rather than upward, and when they occur along vertical fractures he does not suggest their continuation below the Blue limestone, but simply argues against their immediate derivation from the overlying White porphyry, and is apparently no more a believer in Mr. J. Alden Smith's theory than was the writer. Yet the region he treats of is the one region in Leadville where vertical cracks are most frequently found in connection with ores in limestone, and it is upon their occurrence that Mr. Blow founded his theory of northeast shoots as the prevailing form of Leadville ore bodies. Hence, the assumption of the various treatises on ore deposits that the writer's theory as to the source of the metals has been disproved by Mr. Blow seems to have been founded on an unfortunate misconception of the facts.

On the other hand, with regard to the ultimate source of the metals, it does not appear from his text that Mr. Blow is entirely clear in his mind as to what that source was, or as to the process by which the vein minerals were derived from it. In one place he says[c] that "it does not necessarily preclude the theory that the porphyries were the derivative rock mass from which the ascending solutions receive their metallic contents, * * * to be ejected subsequent to the porphyries, and consequent upon their intrusion;" and later that the "solutions were forced up with their mineral contents from the deep, from

[a] Mon. U. S. Geol. Survey, vol. 12, 1886, p. 541.
[b] Ibid., p. 573.
[c] Trans. Am. Inst. Min. Eng., vol. 18, 1890, p. 181.

the same regions and in the same manner as that of the intrusive dike porphyries with which they are here and elsewhere so intimately connected." Mr. Blow frankly agrees with the writer, however, in admitting that the theory that the solutions came from below is not susceptible of direct proof; hence, the real difference between him and the writer is that the one was willing and the other was unwilling to put forward views in support of which he could bring no facts of observation.

MODERN VIEWS ON ORE DEPOSITION.

In more recent times, as the knowledge of ore deposits, through scientific studies, has increased, and the more theoretical questions with regard to them have become frequent subjects of discussion, many important changes have been brought about in the views generally held with regard to the origin and manner of formation of ore deposits. It has been actually demonstrated:

1. That deposits in limestone have been formed by directly ascending solutions, of which those of Rico, Colo., are the most notable instances.

2. That certain deposits in limestone have been formed primarily by direct emanations of mineral-bearing solutions from intruded igneous masses during cooling and consolidation, to which alone the term contact deposits is now considered to be scientifically applicable, since they are characterized by the presence of minerals formed during what is known as contact metamorphism. Up to 1901 there were no published scientific descriptions of such deposits in the United States, but since that time a vast number of important deposits, especially of copper, have been described as properly belonging to this type.

3. That certain deposits, especially of magnetic iron, have been actually formed by magmatic segregation from igneous masses during their cooling and consolidation.

4. That underground waters, which are still regarded as the most important vehicle for the transportation of vein material within the earth's crust, are not necessarily all of meteoric origin, as was formerly thought, but may rise from the squeezing out of occluded water from igneous magmas as they cool and contract. That such magmas are giving out water in sufficient quantity to feed thermal springs or to form ore deposits is of course not susceptible of direct proof. It has long been recognized that during volcanic eruptions great quantities of the vapor of water escaped into the atmosphere, but this phenomenon has hitherto been explained as the result of the descent through fissures of ocean waters that came into contact with the rising magmas and thus produced extensive eruptions. Suess, the most prominent advocate of the modern theory, claims that it is not the ocean that feeds volcanoes, but that volcanoes have furnished water to

the ocean. Indirect arguments in favor of this theory are found, first, in the observed fact that in very deep mines the lowest levels are relatively or absolutely dry; whence it is assumed that if surface waters do not reach such comparatively shallow depths they can hardly be supposed to have been the vehicle which brought the metals up from the barysphere, which must be fifty or a hundred fold as deep, or even to have reached any very deep-seated cooling magma. Second, European geologists, who have been making very long and thorough chemical studies of thermal waters, claim to be able to distinguish among them, by the relative permanence of their chemical composition and degree of saturation, those which are fed exclusively by cooling magmas, or what Suess calls juvenile waters, from those which are fed exclusively from meteoric waters, or vadose springs, or, again, those which are fed in part from one and in part from the other source.

5. Finally, it is generally admitted that the ores as now found in an ore deposit may be the result of a solution and reprecipitation many times repeated, each process resulting in a concentration of its metallic contents. Most important of these, from an economic view, is the secondary enrichment by surface waters. This was noted by the writer in his original report, as applied to the oxidized ores, but it was not then supposed to be possible chemically that it might go on below the ground-water level in the sulphide zone. This has recently been demonstrated, however, by actual laboratory experiments, and the action is recognized as the most important factor in forming the bonanzas of exceptionally rich deposits.

PRESENT VIEWS OF GENESIS OF LEADVILLE LIMESTONE ORES.

It may be assumed that economic geologists now generally agree, without much qualification, that the limestone ores in the Leadville district were originally deposited—

1. From aqueous solutions.
2. In the original form of sulphides.
3. By metasomatic replacement of the country rock.

Age.—These ores were deposited after the porphyry sheets were intruded and consolidated, but before the dynamic movements which produced the great structural faults of the region. Geological investigations made since the original report was prepared have led to the conclusion that the great preliminary fault movement may have taken place at the close of the Jurassic period, or previous to the beginning of Cretaceous sedimentation, and inasmuch as it must logically be assumed that the structural faulting in the Leadville district was contemporaneous with that of the Mosquito fault the ores in limestone may have been originally deposited in pre-Cretaceous time.

It is further recognized that a small amount of deformation of the sedimentary beds must have taken place at the time of the intrusion of the porphyry sheets, which produced some slight folding and fracturing of these beds, and thus commenced the localization of the ore bodies.

That there has been movement in comparatively recent times along the great structural faults, as was originally stated, has now been definitely proved. Underground exploration has shown that the comparatively recent rhyolitic tuffs and agglomerates are much more widespread in the district than was indicated on the original map. They have cut through and split important ore bodies, but have apparently been confined to the region around Breece Hill, and have not affected the limestone deposits in the lower part of the district.

Distribution of ore.—It was originally assumed, on evidence then available, that the Blue limestone was exceptionally favorable to the deposition and concentration of ore, but it was also stated [a] "that valuable deposits are occasionally found elsewhere, generally along bedding planes or contact surfaces, and less frequently on jointing planes."

Mining developments since that time have shown that the predominance of ore bodies along the upper contact of the Blue limestones is by no means so great as was originally supposed, some of the most important ore shoots having been found within its mass at points away from that contact, generally under the sheet of Gray porphyry, but also within the mass of the White limestone. These are locally called second- and third-contact bodies, respectively. Ore bodies also occur within the Parting quartzite and in the upper part of the Cambrian quartzite. No important and rich ore deposits have been found, however, within the purely siliceous beds at the lower part of the Cambrian, nor at the contact of the latter with the crystalline complex or Archean, such as J. Alden Smith thought would "be extensively and profitably worked for centuries after the contact deposits now operated would be exhausted."

It should be further remarked that the important deposits of gold ores in and adjoining fissure veins in the Breece Hill region are not included in the present discussion, which is confined to the limestone ores treated of in the original report, since their genesis is considered to be distinct and more or less independent of the latter, and will be discussed at length in the general report.

As regards the areal distribution of the principal ore bodies, it bears an evident connection with that of the later intrusive or Gray porphyry sheets, the details of which can not be finally worked out

[a] Second Ann. Rept. U. S. Geol. Survey, 1882, p. 237.

until the general geological map of the district is finished. It would appear at present, however, that where these intrusive bodies have distinctly broken up from below, across the sedimentary beds, as have those that form the mass of Breece and Dome hills, the ores in limestone tend to form around the periphery of such masses.

Immediate source of the metals.—In considering the source or origin of the metallic contents of the ore it seems well to preserve the distinction originally made by the writer between the *immediate* and *ultimate* sources, although this distinction has been ignored by subsequent writers. General treatises can not go into the minute details of structure involved in a consideration of the immediate source, but must be confined to the broader features in their bearing on general theories. Moreover, few, if any, of their authors have ever visited this district, much less made detailed studies of the geological relations of its deposits. On the other hand, the mining engineers, whose opportunities of studying the details of the ore bodies that come under their observation were unquestionably much superior to those of the writer, not being professional geologists and having worked in a relatively limited field, may not have noted the bearing on general theories of all the geological facts that came under their observation.

The determination of the immediate source of the ores is important, even though it may not necessarily affect that of the ultimate source, inasmuch as it furnishes data of practical use to the miner in his search for ore. Thus, in the present case, it would appear that the conception of the authors of general treatises who maintain that the ores were brought in by hot ascending solutions from some deep-seated source is that in their upward course these solutions were stopped by a relatively impermeable barrier, in this case the overlying porphyry sheets, and hence spread out laterally, depositing their contents in the limestone underlying these porphyries. In such a case one would expect to find cracks or fissures extending more or less vertically downward from the respective ore bodies which might have constituted the channels through which the solutions ascended directly to the porphyry contact.

On the other hand, if the ore-bearing solutions, in the latter part of their circulation or immediately before they deposited their contents in the form of the present ore bodies, were moving along the contact planes between porphyry and limestone, they could react on the soluble limestone from these contacts outward and form ore bodies, either along the immediate contact or at points within its mass, reached through cracks and joints. On this hypothesis, if most of the contact ore bodies were found under the porphyry sheet, the prevailing course of the ore solutions would have been downward, and such

solutions might have formed ore bodies on the upper contact of a lower sheet, because that sheet presented a barrier to their downward course.

As regards the ultimate source of the ores, while the former of these hypotheses is more peculiarly applicable to the deep-seated source, the latter is not inconsistent with the derivation of the metals from either the barysphere or from igneous masses within limited distances of the ore deposits.

Leaving entirely out of consideration, for the moment, the question of the ultimate source of the metals, the evidence as to their immediate source must first be considered, since, from the writer's point of view, that is the only one really involved in the criticisms of his original report. In favor of the first, or what might be called the "fissure hypothesis," is the discovery in recent years of deposits coming from or directly connected with vertical fissures in the Breece Hill region, which, however, according to the writer's view were formed in a distinct and different manner from the deposits in limestone in the lower part of the district, which are now under consideration. In the latter deposits the writer has been unable to find evidence which seems to him conclusive in favor of the fissure hypothesis, or which might not be as readily interpreted in favor of contact and stratification planes as channels for the ore-bearing solutions. Cracks and broken or fissured zones are, it is true, found in connection with some of the limestone ore bodies, especially with ore bodies that have a decided linear arrangement, such as the ore shoots on South Iron Hill, described by Blow. In a broad, general way, these shoots lie in two prominent or major directions—a northwest-southeast direction, which prevails on Iron and Breece hills, and an east-west direction, which is more prominent in the northwest portion of the district. These apparently correspond to those of the axes of slight folding and fracturing that took place about the time of the intrusion of the porphyry. The structural conditions accompanying these fissures do not resemble however, those connected with the limestone deposits of Rico, Colo., which may be taken as the type of those formed by solutions that ascended through fissures. At Rico the feeding fissures contain well-defined and crustified vein deposits. They end upward at a bed of impervious shale that overlies the limestone, but no limit in depth has yet been found. Under the shale, ore bodies called "blankets" spread out horizontally in the limestone, following a zone that is at some places brecciated along the general direction of the fissures. It has been generally assumed in this case that the ores in the blanket deposits were deposited by waters ascending along the fisures, but Ransome, who made the latest and most detailed study of the district, thinks they are due to the mingling of these with solutions that moved laterally along the blanket zone.

In the Leadville limestone only small cracks have been observed in connection with the ore bodies. Many of these cracks are traceable upward from the tops of the ore bodies to the overlying porphyry, but, so far as known to the writer, do not extend downward much below the workable ore bodies. A similar conclusion might be drawn from Mr. Blow's description of the Iron Hill ore bodies, for when he prophesies that their extension will be found at a lower horizon, he expects them to go down not vertically but transversely across the stratification, and, as stated above, he believes that the ore solutions entered the limestone along the contacts of Gray porphyry sheets. His improper use of the word "dike" to denote crosscutting sheets has given rise to the idea that he supposed the solutions to have risen vertically along actual dikes to the present ore bodies.

It is evident that the fractures that cross the limestone have played an important part in fixing the location of ore bodies and in furnishing channels along which the ore-bearing solutions may pass from one horizon to another, but the general impression produced upon the mind of the writer has been rather that they served to divert or temporarily to arrest horizontally moving solutions (especially where, as can sometimes be proved, they are the final result of a strain that produced folding) rather than afforded continuous channels for solutions moving directly upward.

The relative superposition of ore bodies at different horizons in a given region is, furthermore, such as to suggest that they were formed by solutions that circulated along contacts and bedding planes, and, incidentally, in joints and cracks that crossed the latter, rather than directly upward through a common vertical fissure that fed a series of superposed ore bodies.

There is, moreover, an absence of evidence in the mineralogical composition of the ores and wall rocks that these ore-bearing solutions had temperatures that were high enough to render their direct upward course inherently probable.

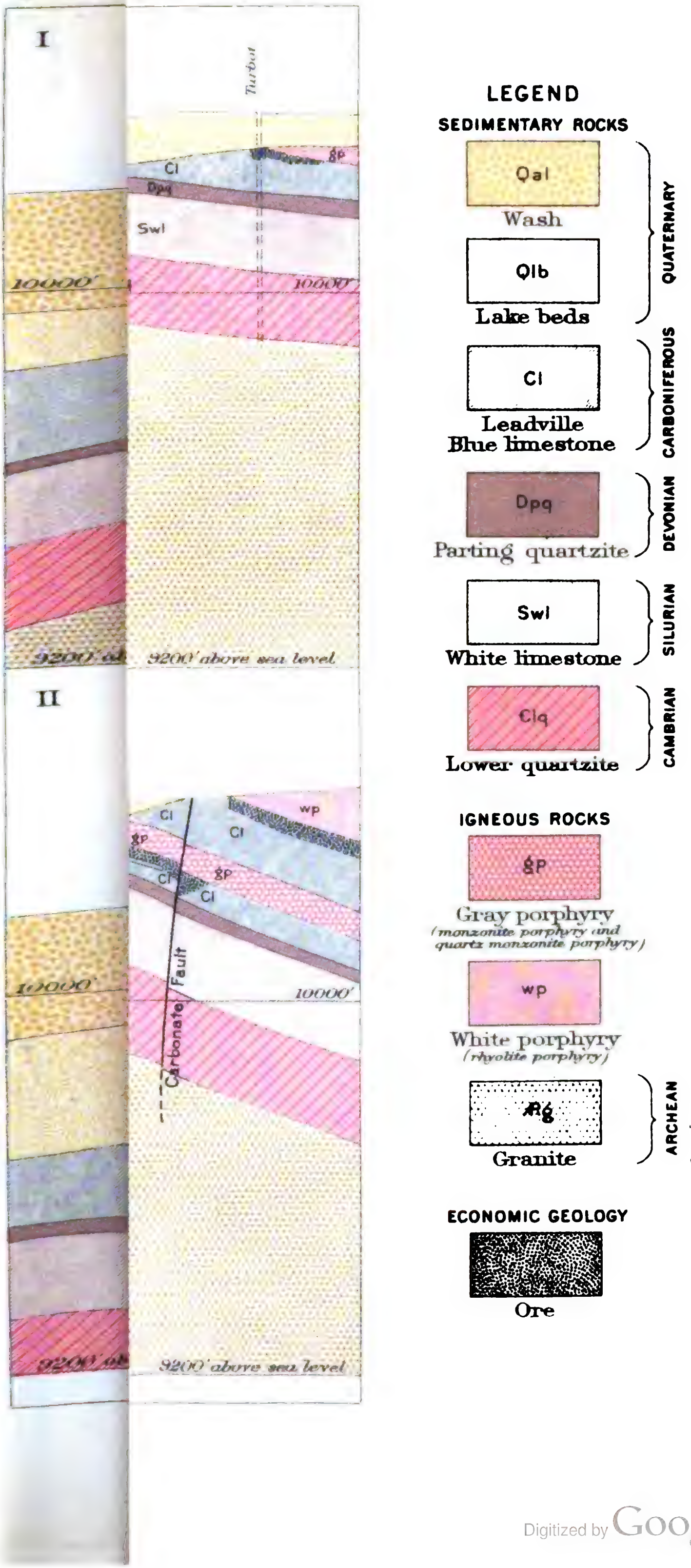
Ultimate source of the metals.—The writer does not consider it appropriate in this place to go at length into the theoretical question of magmatic versus meteoric waters, which has been abundantly discussed of late in special articles and treatises, an increasing importance being given by many of our best students of ore deposits to the agency of magmatic waters in the formation of ore deposits which may be genetically connected with igneous eruptions. It seems better to postpone the discussion of the broad question of the ultimate origin of the metallic contents of the Leadville ore deposits until the map of the whole district shall have been completed rather than to attempt it in connection with the present description of a comparatively small portion of the area, in which the oxidizing agents have obscured much of the evidence. The original contention that

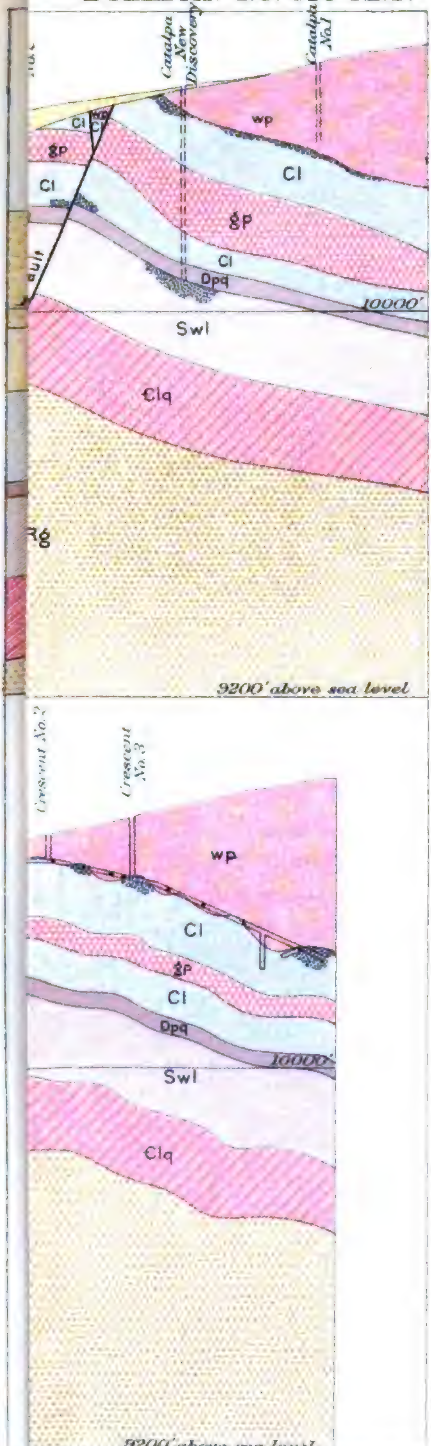
the ores are genetically connected with the eruptive rocks seems abundantly confirmed and even strengthened by the development of the last twenty-five years. That their concentration in exceptionally rich bodies has come about through the agency of surface waters is also confirmed, and the study of the sulphide bodies has shown that this secondary enrichment has not been confined to the oxidized zone, but has extended below the ground-water level. The questions still at issue are:

1. Whether the sulphide ores were originally deposited as a precipitate exclusively from meteoric or from magmatic waters, or in part from both.

2. Whether the magmatic waters, if they were the transporting agents, reached the present locus of the deposits directly from below, or whether they came up along the general channels that carried the magma of the intrusive rocks, and, where this magma had spread out in sheets between the sedimentary strata, whether they followed in general the contacts between intrusives and sedimentaries or penetrated the mass of the latter along cracks and joints before depositing their load.

3. Whether the deposits, or any part of them, were formed by contact metamorphism—that is, by waters emanating directly from the cooling intrusive bodies, squeezed out, as it were, from the solidifying igneous mass into the adjoining sedimentary beds.


I
Turbut
Cl
Dpq
Swl
gP
10000'
9200' above sea level
II
wp
Cl
gP
Carbonate Fault
10000'
9200' above sea level
LEGEND
SEDIMENTARY ROCKS
Qal
Wash
Qlb
Lake beds
QUATERNARY
Cl
Leadville
Blue limestone
CARBONIFEROUS
Dpq
Parting quartzite
DEVONIAN
Swl
White limestone
SILURIAN
Clq
Lower quartzite
CAMBRIAN
IGNEOUS ROCKS
gP
Gray porphyry
(monzonite porphyry and quartz monzonite porphyry)
wp
White porphyry
(rhyolite porphyry)
Ag
Granite
ARCHEAN
ECONOMIC GEOLOGY
Ore



LEGEND

SEDIMENTARY ROCKS

QUATERNARY
- Qal — Wash
- Qlb — Lake beds

CARBONIFEROUS
- Cl — Leadville Blue limestone

DEVONIAN
- Dpq — Parting quartzite

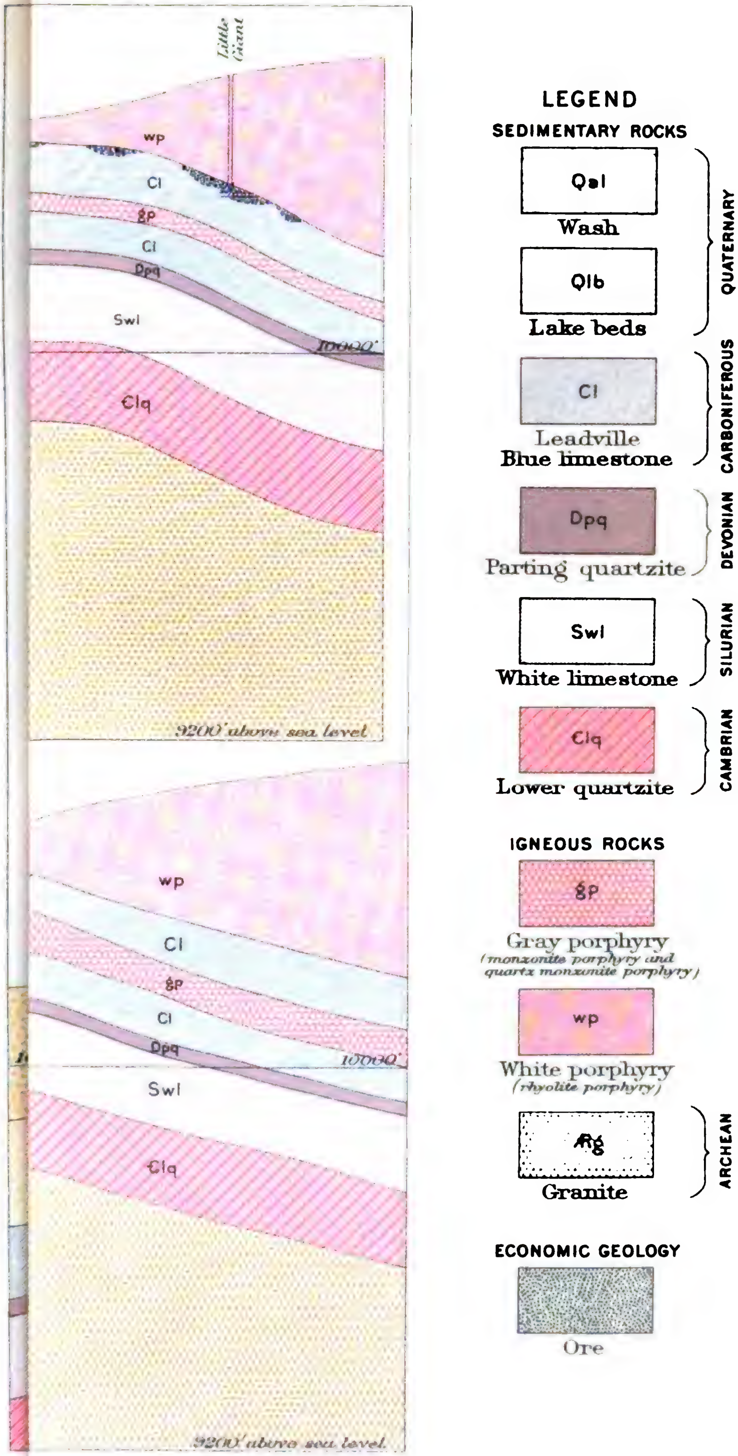
SILURIAN
- Swl — White limestone

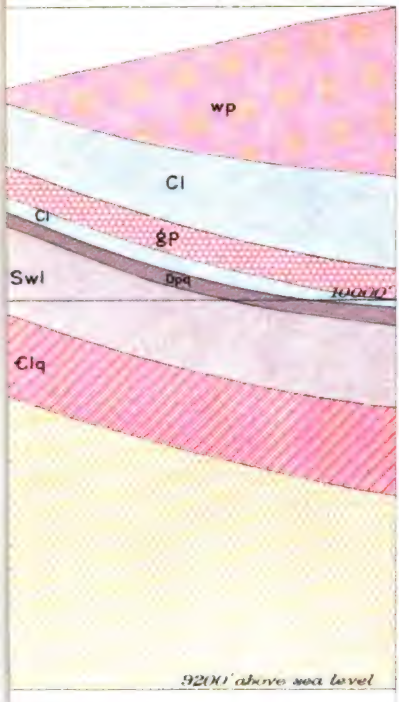
CAMBRIAN
- Clq — Lower quartzite

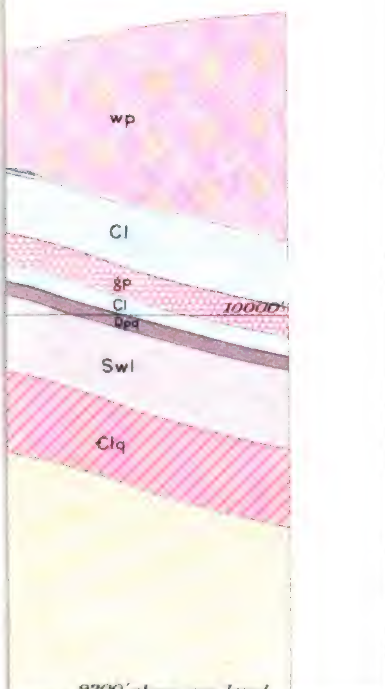
IGNEOUS ROCKS
- gP — Gray porphyry (monzonite porphyry and quartz monzonite porphyry)
- wp — White porphyry (rhyolite porphyry)

ARCHEAN
- Rg — Granite

ECONOMIC GEOLOGY
- Ore


Little Giant
wp
Cl
gP
Cl
Dpq
Swl
10000'
Clq
9200' above sea level
wp
Cl
gP
Cl
Dpq
10000'
Swl
Clq
9200' above sea level
LEGEND
SEDIMENTARY ROCKS
Qal
Wash
Qlb
Lake beds
QUATERNARY
Cl
Leadville Blue limestone
CARBONIFEROUS
Dpq
Parting quartzite
DEVONIAN
Swl
White limestone
SILURIAN
Clq
Lower quartzite
CAMBRIAN
IGNEOUS ROCKS
gP
Gray porphyry
(monzonite porphyry and quartz monzonite porphyry)
wp
White porphyry
(rhyolite porphyry)
Rg
Granite
ARCHEAN
ECONOMIC GEOLOGY
Ore





LEGEND

SEDIMENTARY ROCKS

QUATERNARY
- Qal — Wash
- Qlb — Lake beds

CARBONIFEROUS
- Cl — Leadville Blue limestone

DEVONIAN
- Dpq — Parting quartzite

SILURIAN
- Swl — White limestone

CAMBRIAN
- Clq — Lower quartzite

IGNEOUS ROCKS

- gp — Gray porphyry (monzonite porphyry and quartz monzonite porphyry)
- wp — White porphyry (rhyolite porphyry)

ARCHEAN
- Ag — Granite

ECONOMIC GEOLOGY

- Ore


O'Donovan
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CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 320.]

The publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists can be had on application.

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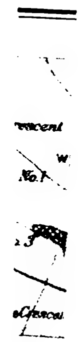

VI

Bulletin No. 321

Series { A, Economic Geology, 102
B, Descriptive Geology, 126

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, DIRECTOR

GEOLOGY AND OIL RESOURCES

OF THE

SUMMERLAND DISTRICT

SANTA BARBARA COUNTY
CALIFORNIA

BY

RALPH ARNOLD

WASHINGTON
GOVERNMENT PRINTING OFFICE
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ILLUSTRATIONS.

GEOLOGY AND OIL RESOURCES OF THE SUMMERLAND DISTRICT, SANTA BARBARA COUNTY, CALIFORNIA.

By Ralph Arnold.

INTRODUCTION.

PRELIMINARY STATEMENT.

One of the most novel and interesting sights along the coast of Santa Barbara County is that of the derricks marking the location of the oil wells which start down from wharves over the Pacific Ocean at Summerland. Mr. George H. Eldridge examined this territory in February and March, 1902, with the intention of incorporating a description of it in his contemplated exhaustive report on the California oil fields; but he died in June, 1905, before he had written anything concerning this field except a very brief note, which was published in Contributions to Economic Geology for 1902.[a] Mr. Eldridge visited the field during the height of its development, and for this reason was able to obtain much valuable information concerning the geology of the wells which otherwise would have been lost. The writer has made free use of this information in the compilation of the contour map and the sections accompanying the present report.

During the summer of 1906 the writer spent two weeks in an examination of the Summerland field and a geologic survey of the contiguous region along the coast from Santa Barbara to Carpinteria and as far inland as the crest of the Santa Ynez Range. In the following pages the discussion of the geology is based almost entirely on the work of the writer. The data concerning the wells have been obtained largely from Mr. Eldridge's notebooks.

So far as the development of the present producing sands is concerned, the Summerland field has undoubtedly passed its acme. However, so much that is of service in drawing conclusions about less well-developed fields is to be learned from a study of a fully

[a] Bull. U. S. Geol. Survey No. 213, 1903, pp. 313-315.

exploited territory like this that it has been deemed expedient to prepare the present more or less detailed report.

A brief summary of the previous knowledge of the region, followed by a fairly full description of its topography and geology, introduces the detailed discussion of the geology of the wells and conclusions concerning future development. This portion of the report is followed by sections devoted to a discussion of the properties of the oil, a statement of production, and data concerned with the technology of the industry. The descriptions of the geology and structure are elucidated by photographic views, drawings, and maps, and plates showing the abundant or characteristic fossils of the various formations supplement the lists in the text.

ACKNOWLEDGMENTS.

To Mr. George H. Eldridge the writer is under the greatest obligation for the free use that has been made of notes and ideas concerning the occurrence of the petroleum. Where sections or direct statements are copied from his notebooks, the fact has been so recorded. The thanks of Mr. Eldridge to those who furnished him with information would certainly have been recorded in his report had he lived to write it, and the present writer feels that he is doing only what his predecessor would have done in recording the names of those to whom, as indicated by his notes, he was indebted. These are Messrs. Snow, of the Occidental Mining and Improvement Company; J. B. Treadwell; G. F. Becker; J. C. Lillis, of the Lillis Oil Company; Thomas D. Wood and R. A. Phelps, of the Duquesne Oil Company; J. E. Sloan, of the North Star Oil Company; J. W. Darling; C. C. Newman, of the Sea Cliff and Oxnard oil companies; W. L. Rust, of the Sea Side Oil Company; C. W. Robinson; G. W. Woodruff; J. H. Lundberg; B. N. Coffman, of the Marine Oil Company; J. F. Miller; A. C. Doane; and presumably several others whose names do not appear. In addition to those mentioned the writer wishes to acknowledge his indebtedness to Messrs. J. F. Goodwin, of the Pinal Oil Company; W. D. Morgan, of the G. F. Becker Oil Company; E. G. Ludlam, manager of the Southern Pacific Company's wells; A. Sattler, manager of the Columbia Oil and Asphalt Company of Carpinteria; F. F. Fluornoy, county surveyor; and Dr. Lorenzo G. Yates, of Santa Barbara. Dr. R. S. Bassler, of the United States National Museum, kindly prepared the plate and explanations of the commoner species of Bryozoa found in the Fernando (Pliocene) beds of the district.

PREVIOUS KNOWLEDGE OF THE REGION.

Several geologists have at one time or another visited the region under discussion, and in the following paragraphs the writer has attempted to give a résumé of the notes recorded by these men.

Those statements which relate to localities in this region not visited by the writer, or which are in publications inaccessible to most readers, are copied more or less in detail. A more complete bibliography of the literature referring to the geology of the southern coast ranges and the oil industry in California will be found in Bulletin No. 309 of the United States Geological Survey, pages 199–202. The following references are arrranged chronologically:

1853. Blake, W. P., Report of a reconnaissance and survey in California, in 1853.[a] So far as the writer is aware, W. P. Blake, one of the geologists of the Pacific Railroad survey, was the first to give any notes concerning the geology of the region about Santa Barbara. According to Antisell,[b] Blake, in describing the Santa Ynez Range, "puts forth the view that all of these strata from Point Arguello eastward have been elevated by the mass of granite forming the San Bernardino Mountains, whose influence he believes to spread thus far to the west, and also to have produced the lone hills of the desert and basin upon the east."

1855. Trask, J. B., Report on the geology of the Coast Mountains, etc.[c] Trask, first State geologist of California, was the next writer to describe the Santa Barbara country, and he, too, adopted the same view of the origin of the Santa Ynez Range as Blake, and even went so far as to include the range under the name "San Bernardino Mountains."

1857. Antisell, Thomas, Santa Barbara Mountains.[d] Antisell, in his description of the geology of the Santa Barbara Mountains, was the first to call attention to what is believed by the writer to be one of the most important points regarding them. He says:[e]

> Between the disposition of the Sierra Santa Ynez and that of the more easterly coast ranges there is this difference—that while the other ranges are disposed so by virtue of their axial forces running along the direction of that range, the Santa Ynez Mountains are ridges en échelon, interlocking with each other, and running from east to west.

This statement is true more particularly for the western portion of the range, physiographic and structural axes being approximately coincident in that part immediately back of Summerland.

Antisell doubtless was mistaken as to the origin of one or two of the rocks he describes, but in the main his descriptions of both the igneous and the sedimentary rocks of the range are correct. The most interesting part of his report, from the standpoint of one interested in the oil industry, is the chapter devoted to "bituminous effusions."[f] In this he describes the asphaltum deposit on the Hill

[a] House Doc. No. 129 (fide Antisell, 1857).
[b] Antisell, Thomas, Pacific R. R. Repts., vol. 7, 1857, p. 66.
[c] Senate Doc. No. 14, Sacramento, 1855. 95 pp. (fide Antisell).
[d] Pacific R. R. Repts., vol. 7, pt. 2, 1857, pp. 65–74.
[e] Op. cit., p. 66.
[f] Op. cit., pp. 107-114.

ranch, 6 miles west of Santa Barbara, and the deposit near Rincon Creek, east of Carpinteria. He failed to record the occurrence of the bituminous sands where Summerland now is, or of the deposits at Carpinteria.

1865. Whitney, J. D., Geology of the Coast Ranges from Buenaventura to Gaviota Pass.[a] By far the best description of the geology of the region about Santa Barbara found in any of the older publications is that by Whitney, the second and last State geologist. Those portions of his narrative which pertain to areas not visited by the writer will be given in detail. The descriptions are given in the order in which the localities were visited by his party, which journeyed westward from Ventura to Gaviota and thence northward across the Santa Ynez Mountains.

From Ventura to Carpinteria the strip of land along the southern face of the mountains and between the mountains and the shore appears to be made up entirely of bituminous shales.[b]

> High bluffs or steep hills skirt the coast, showing everywhere inclined strata, dipping from 25° to 30° to the southwest, with a few feet of horizontal beds of detrital material on the top. The slates [shales] are interstratified with fine-grained sandstones, and the formation is undergoing rapid denudation from the action of the resistless surf of the Pacific. The worn edges of the strata, planed off and polished by the waves, may be seen for some distance out from the shore at low water. The strike of these rocks is here from N. 45° to 55° W. No eruptive rock was seen here, and only a few granite bowlders were observed on the beach; but immense numbers of sandstone pebbles were seen, some of which were quite fossiliferous.
>
> About 5 miles southeast of Carpinteria the rock presents exactly the appearance of having had the bituminous matter burned out of it; it assumes various colors, such as bright red, rose, brown, yellow, and cream color, and it appears to have been partially fused in some places. These colors are made very conspicuous by the washing and smoothing of the rocks by the ocean.
>
> The slates [shales] are black and highly bituminous where the outcrop strikes the sea, 3 miles to the southeast of Carpinteria, and large quantities of tarry asphaltum flow from them. For a mile or more along the shore the banks abound in it, and it saturates the beach sand and flows down into the sea.

The bituminous shales and asphaltum deposits in the vicinity of Carpinteria are then described, together with a note on the "oil works" at that place:[c]

> An establishment for distilling oil from the asphaltum was started shortly before the time our party visited the place (March, 1861), but access to it was not allowed nor information given. It is believed, however, to have been a failure, both as regards the quality of the oil produced and the profits of obtaining it.
>
> These bituminous slates [shales] extend along the base of the Santa Ynez Range to the west and were explored by our party as far as the Gaviota Pass, about 45 miles from Carpinteria; they continue beyond this, but, it is said, not as far as Point Conception. The general dip along this line is to the south; but the strata are exceedingly contorted, being bent and twisted into every possible variety of curve. They

[a] Geol. Survey California, Geology, vol. 1, 1865, pp. 125-135.
[b] Op. cit., pp. 125-126.
[c] Op. cit., pp. 126-127.

are also metamorphosed and hardened, and the variations of hardness and color, as well as the elaborate curvings of the beds, are beautifully displayed in the broad. level surface worn off by the sea, and left visible at low tide. These contortions seem to be limited to a rather narrow belt near the shore. As we recede inland they become less conspicuous, and the strata regain gradually their regular southern inclination.

Here follows a general description of the extent of the Santa Ynez Range and its salient geologic features, together with a description of the hot springs northeast of Santa Barbara. Three geologic sections elucidate Whitney's conception of the geology of the range—one extending across it from the coast to a point north of Carpinteria, another from the coast to Santa Ynez River through Hot Sulphur Springs, and a third from a point on the coast west of Santa Barbara, through the Mission, and thence up toward the top of the range. Continuing the description of the range, Whitney says: "Metamorphic rock and conglomerate were seen on that [north] side, as also serpentine at the north base of the ridge."[a]

Whitney's description of the region west of Santa Barbara[b] is given in its entirety, as it contains matter of much historic interest; furthermore, the writer has been over but a small portion of this country.

Wherever the [Santa Ynez] chain was examined to the west of the section last given [northeast-southwest through the Mission], as far as a point a few miles to the west of Gaviota Pass, the rock had always a dip to the south, at a high angle, the crest consisting of the broken edges of the sandstone, the bituminous slate [shale] resting on its flanks in the foothills, and both formations appearing entirely conformable with each other.

The bituminous slate [shale] is admirably exposed all along the seashore for several miles to the west of Santa Barbara. At a point 1 mile in that direction, where the shales were planed down to the level of the ocean and the stratification could be most beautifully seen, the strike was noticed to be N. 79° E. and the dip 60° to the south. In some places the slate [shale] forms low cliffs by the edge of the ocean; in others it has been denuded, and it is now covered by a more recent deposit. The complication of the disturbances in these strata may be well seen * * * along the base of the bluff. * * * These disturbances seem particularly common in the immediate vicinity of Santa Barbara. In some localities the rock has evidently been on fire, and the bituminous matter having been burned out—the operation continuing for several years, as it is said—the slates [shales] are left of various shades of red, produced by the oxidation of the iron.

The asphaltum, or hardened bituminous matter, occurs in the greatest abundance on the shore at Hill's ranch, about 6 miles west of Santa Barbara, and lies along the beach for a distance of a mile, in large masses. The bituminous slate [shale] is here covered unconformably, as at Santa Barbara, by a heavy deposit of post-Pliocene age, which here attains a thickness of from 80 to 100 feet. * * *

The bituminous slates [shales], which are highly contorted and turned up on edge, lie nearly on a level with the ocean. On their edges rests a body of soft arenaceous and loose gravelly materials, sometimes very slightly consolidated, in which are long fissures filled with asphaltum; this in some cases has risen to the surface of the formation and become accumulated, in large masses, in the overlying recent or alluvial formation. The gradual erosion of the cliff has exposed large masses of the asphaltum which have fallen down and accumulated in considerable quantity on the beach.

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[a] Op. cit., p. 129. [b] Op. cit., pp. 131-134.

* * * This locality has, for a long time, furnished all the asphaltum used for roofs and pavements in San Francisco, as it lies most convenient to the sea. In 1861 this material was sold in the city for $15 per ton, the chief expense of obtaining it being that arising from the difficulty of getting it on board the vessel, on a coast exposed to the Pacific swell. It will be noticed that the asphaltum lies in the arenaceous rock or sandstone, over the bituminous shales, from which it was derived, and from which it has been forced out probably by heat and pressure. Through the slates [shales] themselves the bituminous material appears to be uniformly diffused, and not concentrated into pure masses. The asphaltum, as it lies on the shore, is necessarily much mixed with sand; specimens selected as of fair quality contained about 60 per cent of that material. No appearances of any soft, liquid, or tarry matter were noticed at this locality.

Extending westward from Hill's ranch, the bituminous slate [shale] occupies a strip from 1 to 3 miles wide, between the rugged Santa Ynez Range and the sea. It forms rounded hills, very green and grassy, the soil being fertile and retentive of moisture. The junction of the slates [shales] and sandstones could be accurately traced on the surface by the character of the soil and vegetation, as well as by the form of the hills. In ascending from the sea toward the interior, the chaparral, indicating a dry soil, is first met with on striking the sandstone. The ocean fogs help to supply this region with moisture, and few ranches in California can equal in beauty and fertility those situated on the bituminous slates [shales] along this part of the coast. Of these, the ranches of Mr. Hill and Doctor Denn (Dos Pueblos) and the Rancho El Capitan are the most noted. At the Tortegas ranch the belt of slate [shale] is narrower, appearing to be about 1½ miles wide, which width it holds as far as we traced it, to beyond the Gaviota Pass. Throughout the whole of this extent it has a strike nearly parallel with that of the chain, and everywhere a southern dip, conformable to that of the sandstone which underlies it. At one locality, a short distance west of camp 20, in the cliffs at the base of the ranch called El Capitan, the sea has made a section very nearly at right angles to the strike, and the dip is seen to be quite uniform, being everywhere from 30° to 40°. A portion without apparent break or fault was measured along the bluff on the beach, which represented a perpendicular thickness of about 1,300 feet of slate [shale]. The actual thickness is, however, much greater, probably more than twice as great; but, owing to breaks and faults, this is the greatest thickness measured in any one place, where the rocks were unquestionably not folded, and where the whole could be minutely examined. This portion of the slate [shale] seemed less bituminous than that at Santa Barbara, but still it was, in places, highly charged with this substance.

The last paragraph relating to the environs of Santa Barbara describes the fossiliferous Pliocene and post-Pliocene deposits found along the coast.

1882. Peckham, S. F., Examination of the bituminous substances occurring in southern California.[a] No other of the earlier writers has taken a more optimistic view of the oil industry of California or has more clearly foreseen its possibilities or more intelligently described the surface occurrence of the bituminous products than Professor Peckham. Here are his opening paragraphs in the paper referred to above, written in June, 1866:

To speak seriously of the "oil interests of southern California" draws forth from the majority of the citizens of this State a smile of incredulity or ridicule. To urge their claims to consideration as a field for profitable investment presents to most men strong

[a] Geol. Survey California, Geology, vol. 2, Cambridge, Mass., 1882, appendix F, pp. 49-90.

reasons for doubting your sanity. Yet the southern portion of this State has veritable oil interests, which only need the fostering care of men of sound judgment, aided by sufficient means, to enable this section to ultimately furnish this entire Pacific coast with both illuminating and lubricating oils, at prices that will render futile all competition of eastern products.

Such are the facts as they exist to-day; but, at the same time, with the great mass of this community, and, it may be said, with that of the entire country, so far as it has at any time received attention, this interest was never more depressed in commercial value than at present. The only reason that can be assigned for such an anomalous condition is the fact that real merit has been obscured and rendered contemptible by excessive falsehood and exaggeration, and that a natural production, capable of profitable development, has been made an object of distrust and suspicion by false definitions and spurious representation.

Farther on in this paper[a] the asphalt deposits and bituminous formation exposed east of Point Conception and in the neighborhood of Bigg's ranch, at Rincon Point, are briefly described, and under the heading of "Chemical investigations,"[b] the chemical properties of the oil and asphalt of Santa Barbara, Ventura, and Los Angeles counties are carefully described.

1884. Hanks, Henry G., The minerals of California.[c] Mention is made of the Carpinteria asphalt deposits on page 287 of this report.

1887. Finch, W. W., Infusorial earth at Santa Barbara, Cal.[d] This short paper consists of brief descriptions of the diatomaceous deposits north of Santa Barbara, together with some general information concerning diatoms.

1888. Goodyear, W. A., and Weber, A. H., Petroleum, asphaltum, and natural gas in Santa Barbara County.[e] This report sums up the development work done in the county, which includes wells put down at Summerland by H. L. Williams on Ortega Hill, another well put down ten years previous on the flat at the foot of the hill, two wells sunk by the "Santa Barbara Oil Company" in Oil Canyon in 1885, and a well sunk 3 or 4 miles north of Carpinteria. In addition there are brief descriptions of the asphaltum deposits at Carpinteria and east of Goleta (Hill's ranch).

1890. Ford, H. C., Solfataras in the vicinity of Santa Barbara.[f] As this paper contains considerable data having not only a local but a general bearing on the subject of the burning of the bituminous shales, and is published in a bulletin inaccessible to most people interested in the subject, it has been deemed advisable to reproduce a considerable portion of it here:

The second group of "fire wells" visited are about three-fourths of a mile below a point where the Rincon Creek enters the sea and near the carriage road and railway

[a] Op. cit., pp. 50-51.
[b] Op. cit., pp. 73-90.
[c] Fourth Ann. Rept. California State Mineralogist, 1884, pp. 67-397.
[d] Bull. Santa Barbara Soc. Nat. Hist. No. 1, 1887, pp. 8-11.
[e] Seventh Ann. Rept. California State Mineralogist, 1888, pp. 89-91.
[f] Bull. Santa Barbara Soc. Nat. Hist., vol. 1, No. 2, October, 1890, pp. 53-56.

leading from Santa Barbara to Ventura. Before the grading of the railway was accomplished, the traveler by the beach road might have noticed some peculiar-looking rocks that had fallen from the cliffs above. The rocks appear to have been originally similar to those composing the mass of the exposed portion of the cliff, which are principally light-colored shales, but their character, both in density, specific gravity, and color, has been altered by the action of mineral gases and great heat. Nearly all shades of red, yellow, and brown, and in some cases green, are colors represented. The intensity of the heat at some former period seems to have contracted the strata through semifusion until it is excessively hard and gives a metallic ring when struck with a hammer.

Reaching by an easy path a point about 300 feet above the base of the cliff, I was at once aware of the near existence of the "solfatara," or so-called "Rincon volcano," by the same exceedingly disagreeable odors that were noted in the Santa Ynez issue. Descending 20 or 30 feet, I found hot gases bursting from numerous apertures in the shales, accompanied in some cases by melted bitumen that hardened in concretionary masses upon cooling. The dip of the strata was at an angle of 50° toward the mountain. Crystals of sulphur had also formed upon all objects near the issue, and naphtha appeared to be present. A few years ago a tunnel was run into the cliff at its base to the depth of 200 feet in search of oil. At this depth the workmen were obliged to cease operations in their endeavor to penetrate farther on account of the great heat. Upon entering this tunnel I found the temperature still high, but noticed only weak sulphurous gases. Near the entrance for 50 or 60 feet the roof and sides were thickly covered with attenuated colorless crystals of epsomite hanging in tufts and masses.

During the cooler months, as at the Santa Ynez locality, the gases arising from the principal orifices are seen from distant points, and the issue of so much smoke and accompanying heat has given rise to a popular idea that it is due to volcanic action. The local journals have from time to time given voice to this idea, and the frequency of earthquake shocks in the neighborhood has been attributed to the struggling efforts of the "Rincon volcano." When the excavations of the Southern Pacific Railway were made at a point a mile farther west from the locality just described, a similar issue was discovered, and upon touching a match to the gas combustion ensued and continued, notwithstanding vigorous efforts were made to extinguish it. The fumes caused much annoyance to the laborers, and not until masses of earth were dumped over the orifice did it cease to burn.

During the summer of 1888 Mr. Richardson, who resides a short distance below the Rincon "fire wells," was startled by loud reports in their direction, and upon visiting the locality observed flames issuing to the height of several feet from the apertures. Parties from Santa Barbara visited the spot upon hearing of this outburst and confirmed Mr. Richardson's observations.

Apparently there have been periods of great activity, followed by long intervals of comparative rest. The partially fused rocks, with their altered color and density, would indicate a period of greater intensity of heat than at present prevails.

1894. Fairbanks, H. W., Geology of northern Ventura, Santa Barbara, San Luis Obispo, Monterey, and San Benito counties.[a] This description of the general geologic features of the southern Coast Ranges is the most comprehensive one yet published. The statement is made on page 501 that the main portion of the Santa Ynez Range is Miocene. This is certainly not true for those portions examined by the writer, as in the region north of Summerland and

[a] Twelfth Ann. Rept. California State Mining Bureau, 1894, pp. 493-526.

Santa Barbara the range is largely Eocene (Topatopa). The asphaltum and petroleum deposits of Santa Barbara and vicinity are mentioned on pages 31 and 357, respectively, of the same report. On the latter page is a description of the Occidental wells and the Santa Monica Oil Company's wells north of Summerland.

1897. Watts, W. L., Oil and gas yielding formations of Los Angeles, Ventura, and Santa Barbara counties.[a] In part 3 of this report, devoted to the region between Santa Paula, Ventura County, and Summerland, Santa Barbara County, Watts describes the Punta Gorda asphalt mine east of Rincon Creek; the Las Conchas mine and asphaltum works and the Higgins well at Carpinteria; the Fischer oil wells at Loon Point, near Ortega station; the Occidental oil wells, 5 miles northeast of Summerland; the Santa Monica Oil Company's wells, 2 miles north of Carpinteria, and the oil wells at Summerland belonging to H. L. Williams; Darling & Turner; Alameda and Santa Barbara Development Company; Bachus & Cravens; Cole; Dewlaney; Doulton & Wilson; Forester & Treadwell; Loomis; Moore; Stevens & Roberts; and Darling Brothers; also the Cone gas wells. In addition to the above there is a brief description and résumé of the geologic formations and a geologic sketch map of the field.

1900. Watts, W. L., Oil and gas yielding formations of California.[b] In chapter 1 of part 6, which is devoted to the Summerland oil field and productive wells in Santa Barbara County, Watts describes the development which had taken place since the time of his previous visit in 1895, together with some general observations concerning the geology of the wells, value of the oil, etc., and includes a list of the oil producers and wharf owners at Summerland. Under the heading "Prospect wells in Santa Barbara County" the following wells, found within the Summerland district, are mentioned: Arctic Oil Company's wells Nos. 1 and 2, 7 miles south of Rincon Creek, and No. 3, 1¼ miles east of Carpinteria; Denn ranch wells, 3 miles west of Goleta; J. Heath's well, near mouth of Rincon Creek; Illinois Oil and Asphalt Company's well at Montecito; Robinson well, near Serena; Santa Barbara and Naples Oil and Development Company's well, 15 miles west of Santa Barbara; Stevens, Clark & Duncan well, at Loon Point; and the Treadwell well, between Loon Point and Serena. Some distillation tests of the Summerland oil are given on page 203 of the report. (See table on page 63 of this bulletin.)

1901. Eldridge, George H., The asphalt and bituminous rock deposits of the United States.[c] The general geologic features and the asphalt deposits of the region from Gaviota to Punta Gorda are

[a] Bull. California State Mining Bureau No. 11, 1897, 94 pp., 35 figs.
[b] Ibid., No. 19, 1900, 236 pp., 35 figs., 13 maps.
[c] Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 1, 1901, pp. 209-452, pls. 25-53, figs. 1-52.

described by Eldridge in this report, pages 439 to 446. The deposits in the vicinity of Gaviota, Mores Landing (La Patera mine), Carpinteria (Las Conchas quarry), and Punta Gorda are treated in detail, the text being supplemented by many fine illustrations.

1902. Arnold, Delos and Ralph, The marine Pliocene and Pleistocene stratigraphy of the coast of southern California.[a] In this paper the Packards Hill and Bath-house Beach beds are briefly described and correlated with similar beds at other points along the coast.

1903. Eldridge, George H., Petroleum fields of California.[b] A section of this summary report (pages 313-315) is devoted to a description of the Summerland field. The conclusions reached by the writer agree in the main with those expressed by Eldridge in this report.

1903. Arnold, Ralph, The paleontology and stratigraphy of the marine Pliocene and Pleistocene of San Pedro, Cal.[c] On pages 50 to 54 of this paper the writer describes the Pliocene and Pleistocene deposits in the vicinity of Santa Barbara in more or less detail, supplementing the notes on the geology by lists of the species of fossils. (See p. 32.)

1904. Prutzman, Paul W., Production and use of petroleum in California.[d] In this valuable paper Prutzman devotes a brief section to a description of the Summerland field, together with a statistical table of the number of producing wells, etc., in December, 1903. References to the refinery at Summerland and to the physical and chemical properties and uses of the oil found there are included in the body of the report.

HISTORICAL OUTLINE.[e]

The first oil well in the Summerland field of which we have any record was sunk on the flat one-fourth mile east of Ortega Hill about 1877.[f] This well is said to have penetrated to a depth of about 180 feet and to have encountered quicksand with oil. It was never operated. About ten years later (1887) H. L. Williams sunk two wells, one 455 feet deep, on Ortega Hill. These penetrated two oil sands. In 1891 Darling Brothers drilled a well about 1,200 feet northwest of the Summerland station and obtained a flow of gas under an 8-pound pressure sufficient to supply 17 families with fuel. A year later the same men sunk another well in the same vicinity and obtained similar results. Sometime previous to 1895 two gas wells, known as the Cone wells, were sunk in the northwestern part of Summerland. Between 1891 and 1895 there was considerable activity in the field,

[a] Jour. Geol., vol. 10., No. 2. 1902, pp. 134-135.

[b] In Contributions to Economic Geology for 1902: Bull. U. S. Geol. Survey No. 213, 1903, pp. 306-321.

[c] Mem. California Acad. Sci., vol. 3, 1903, 420 pp., 37 pls.

[d] Bull. California State Mining Bureau No. 32, 1904, 230 pp., 29 tables, 64 half-tones, 54 figs.

[e] Most of the historical data here recorded have been gleaned from Watts's two reports on this field in Bulletins Nos. 11 and 19 of the California State Mining Bureau. (See p. 15.)

[f] Seventh Ann. Rept. California State Mining Bureau, 1888, p. 90.

and by the end of the latter year there were 28 productive wells, which produced 16,904 barrels of oil in 1895. Up to this time the development was confined mostly to the terrace on which the town of Summerland is located, although Mr. Williams had three wells on the beach at the west end of the town.

Stimulated by the success of the wells previously drilled, and doubtless guided somewhat by the suggestions offered by Watts in Bulletin No. 11, the development in 1896 began along the beach and finally extended out toward the ocean, the wells being drilled from wharves built out over the water.

In June, 1900, there were at Summerland 305 producing wells, 59 abandoned wells, and 15 well sites at which drilling operations had been commenced. These wells yield from 1 to 60 barrels of oil a day, the average yield being 5 barrels a day. The value of the oil in 1899 was 90 cents a barrel f. o. b. at Summerland. The cost of production is said to range from 25 to 35 cents a barrel.[a]

There were 22 companies operating and 12 wharves in use in 1899. Development continued up to about 1901 or 1902, at which time there were still about 20 companies in the field. Since 1902, owing to certain adverse conditions of price and marketing, the field has been declining. At the end of 1903[b] there were 198 producing wells, 114 not producing, and 100 abandoned. The approximate price per barrel at that time was 80 cents. At the present time (October, 1906) there are 189 producing wells out of the 412 which at one time or another have been drilled in this field. The companies still operating, 14 in number, are listed on page 67.

LOCATION.

The Summerland oil district is situated in Santa Barbara County, on the coast of California, between 80 and 90 miles west-northwest of Los Angeles and about 350 miles southeast of San Francisco. (See fig. 1.) The region mapped comprises an area of about 52 square miles, in the shape of a rectangle 13 miles in extent east and west along the shore by about 4 miles in width north and south. It includes at its west end the city of Santa Barbara (population 6,587 in 1900), one of the oldest settlements in California, which lies at 34° 25′ north latitude and 119° 42′ west longitude. The district is reached by the Coast division of the Southern Pacific Railroad, which here follows the coast, and by vessels which touch at the port of Santa Barbara. The town of Summerland, at which the only productive oil field so far developed in the district is situated, lies nearly 6 miles east of Santa Barbara.

[a] Bull. California State Mining Bureau No. 19, 1900, p. 103.
[b] Bull. California State Mining Bureau No. 32, 1904, p. 32.

TOPOGRAPHY.

The Santa Ynez Mountains, which extend for over 60 miles from Ventura River to Point Conception, are the dominant topographic feature of the region. (See Pl. I.) These mountains are part of the east-west system of ranges which prevails in the region south of the upper end of the great interior valley of California, and

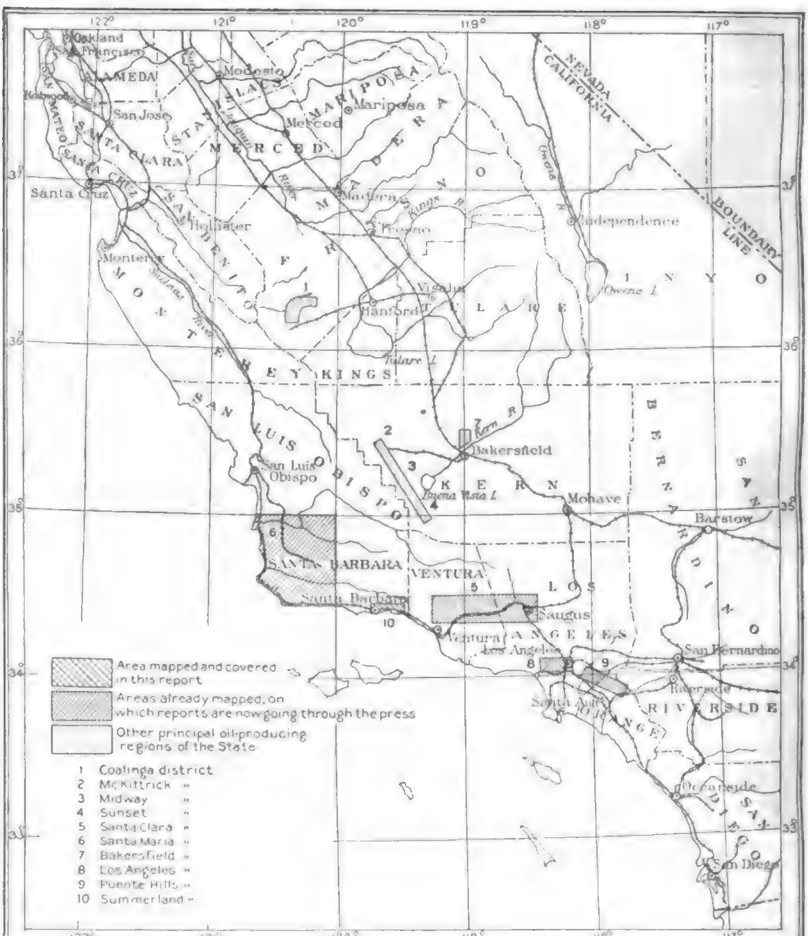
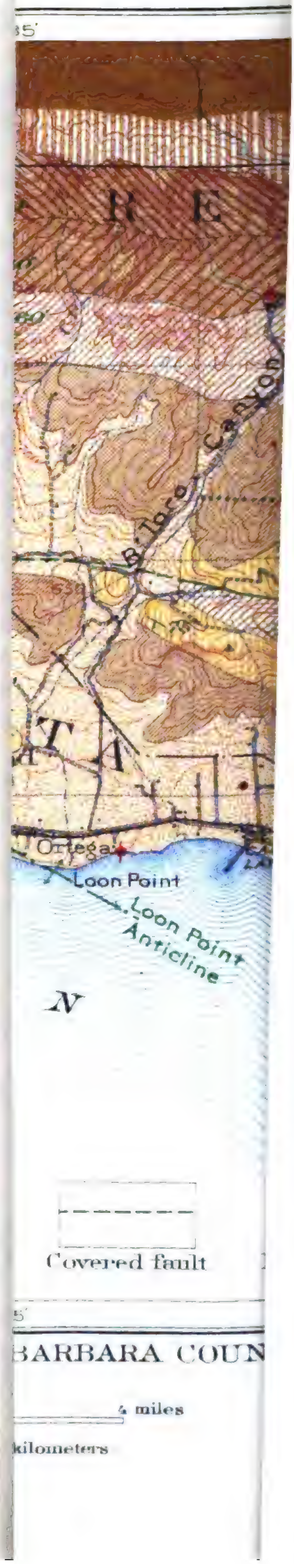


FIG. 1.—Index map of a portion of southern California, showing location of district described in this bulletin and of the other important producing districts of the State.

determines the trend of the coast along this part of the State. They terminate between Points Conception and Arguello, the two salients about which the coast bends abruptly from an east-west to a north-south trend. The mapped area embraces the south flank of that portion of the range lying back of Summerland and Santa



35'
R E
B. Toro Canyon
T A
Ortega
Loon Point
Loon Point Anticline
N
Covered fault
5'
BARBARA COUN
4 miles
kilometers

Barbara. The mountains present a bold, rugged front and a more or less serrate crest, the variation in altitude along the summit being from 3,300 to nearly 4,000 feet. La Cumbre Peak, elevation 3,985 feet, 5 miles north of Santa Barbara, is the highest point in the region.

Many canyons cut the range at right angles; these are steep and narrow and in many places toward their heads have precipitous sides. They usually drain cirque-like basins which lie close to the axis of the main ridge. Streams flow from the larger canyons and debouch over alluvial fans onto the sloping terrace which skirts the coast. In the summer these streams are comparatively small, but during the rainy season they sometimes assume torrential proportions and carry bowlders of enormous size out onto the lowlands for distances of over a mile. The vegetation of the mountains is confined largely to dense growths of chaparral and other brush, with sycamores and alders in the canyons. Live oaks are found over the lowlands in places, especially in the vicinity of Montecito.

Back of both Summerland and Santa Barbara, between the mountains and the sea, are long comparatively flat-topped hills which rise to elevations of 600 to 1,100 feet. These ridges, and the long, low knolls which lie in the Montecito Valley between them, are doubtless blocks which have been faulted up relative to the region on their north. Their north sides, coinciding with the fault zone, are steep, while their south slopes are more gentle.

Mission Ridge, back of Santa Barbara, and the eastward continuation of this ridge beyond Sycamore Canyon, show marked evidence of terracing. These terraces, which are of marine origin, have been subjected to differential uplift since their formation, as is indicated by their varying elevations at different points. The highest terrace, represented by the top of the ridge, is about 850 feet above sea level in its western portion, but immediately west of Sycamore Canyon it is only a little more than 750 feet; just south of the canyon the highest remnant of the same terrace lies at 666 feet, and this slopes off to a little more than 550 feet west of Montecito. This change in elevation of approximately 300 feet takes place in about 2½ miles. On the south side of Mission Ridge there are remnants of old terraces at elevations of 600 feet at the west end and 650 feet at the east end. Traces of terraces can be seen, at elevations of 250 to 300 feet, south of Sycamore Canyon. There are also evidences of terraces in the hills back of Summerland and Serena, but none as marked as those on Mission Ridge.

The lowland along the coast represents an old terrace which is in large part of marine origin. The terrace, or possibly terraces, for there is no direct connection between some of the isolated flats, varies in elevation from sea level to over 150 feet—the latter being

near the light-house 2 miles southwest of Santa Barbara. Ortega Hill and the little hill southwest of Ortega station (see Pl. II, *A*) are local elevations, due, at least in part, to differential elevation of the terrace along lines coincident with anticlinal axes. The surfaces of these old terraces, and also nearly the whole surface of the region adjacent to the base of the Santa Ynez Mountains, are covered by detrital deposits, more or less waterworn (see Pl. II, *B*). These are discussed under the heading "Pleistocene deposits" on pages 33–35.

Estuarine conditions are prevalent along the coast east of Santa Barbara and west of Carpinteria, and indicate local subsidence coincident in time with the elevation which has taken place over most of the coastal belt.

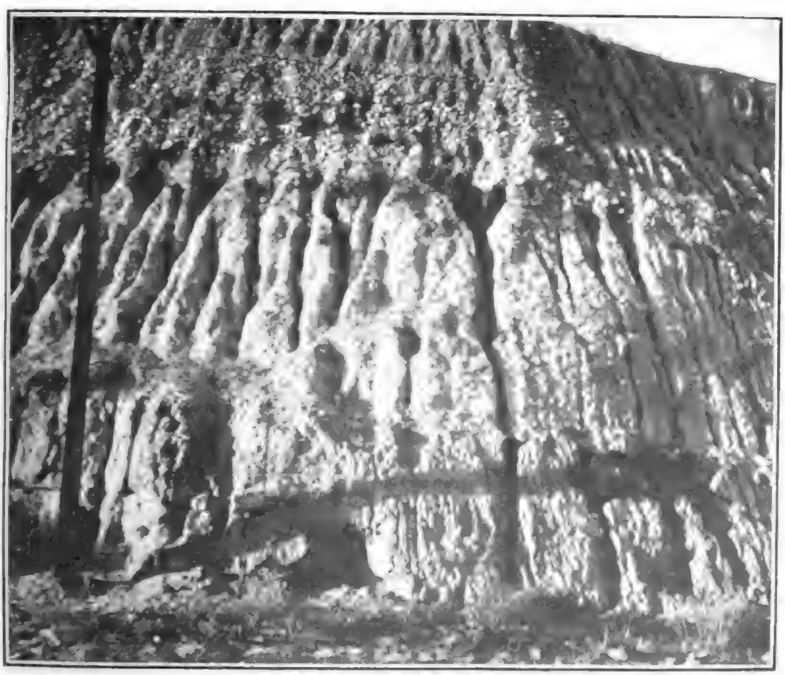
The valley in which the city of Santa Barbara is located is broad, and slopes gradually back from the ocean toward the north and west. The depression is due largely to structural causes, although erosion has played some part in the development of its minor features. The hills bounding this valley on the west are composed of soft Pliocene sediments which have been faulted into their present elevated position, the fault line probably being coincident with their northeastern base.

The local relief in the group of hills back of Summerland has been due in a measure to the composition of the exposed formations, and follows in a general way the strike of the rocks, which is here northwest and southeast. The terrace on which Summerland is situated is a quarter of a mile wide and from 30 to 60 feet in elevation, and slopes gently from the hills to its western boundary, a sea cliff. (See Pl. II, *A*.)

Drainage lines, such as San Roque Creek, Sycamore Canyon, and Toro Canyon, which cut directly through the outer hills, were in existence before the movements which produced the salient local topographic features took place.

A. SUMMERLAND FIELD. FROM ORTEGA HILL, LOOKING SOUTH.

Snowing general configuration of coast, terrace on which Summerland and some of the wells are situated, and location and relative lengths of the various wharves.



B. PLEISTOCENE BEDS IN RAILROAD CUT WEST OF SUMMERLAND. LOOKING NORTH.

Dark sandstone at base is heavily charged with asphaltum derived from overturned oil-bearing Fernando beds below.

GEOLOGIC FORMATIONS.

GENERAL STATEMENT.

The formations involved in the geology of the Summerland district are 9,000± feet of conglomerate, sandstone, and shale of the Topatopa (Eocene); 4,300± feet of conglomerate, sandstone, and shale of the Sespe (Eocene or Oligocene); 2,400± feet of sandstone and shale of the Vaqueros (lower Miocene); 1,900+ feet of shale and volcanic ash of the Monterey (middle Miocene); 1,000+ feet of conglomerate, sandstone, and clay shale of the Fernando (upper Miocene–Pliocene); and 50+ feet of gravel, sand, and clay of the Pleistocene—in all, 18,650± feet of sediments, practically all of Tertiary age. Unconformities occur between the Monterey and Fernando formations and between the latter and the Pleistocene. Reference to the geologic and structural map (Pl. I, p. 18) will elucidate many of the points in the descriptions of the formations which follow.

Tentative correlation of formations of Summerland district with the standard California Coast Range and Santa Clara Valley sections.

Era.	System.	Series.	Standard Coast Range section.	Summerland district section.	Santa Clara Valley section.
Cenozoic.	Quaternary.	Recent.	Alluvium.	Alluvium.	Alluvium.
		Pleistocene.	San Pedro.	Marine and stream deposits.	Sand and gravel.
			Unconformity	Unconformity	Unconformity
	Tertiary.	Pliocene.	Merced.	Fernando.	Fernando.
			Purisima.		
		Miocene.	San Pablo.		
			Unconformity	Unconformity	Unconformity
			Monterey.	Monterey.	Modelo. {Shale. Upper sandstone. Shale. Lower sandstone.
			Vaqueros.	Vaqueros.	Vaqueros.
		Oligocene.	San Lorenzo.	Sespe. {Red beds. Lower sandstone.	Sespe. {Upper. Red beds. Lower.
			Unconformity (?)		
		Eocene.	Tejon.	Topatopa.	Topatopa.
			Martinez.		
			Unconformity (?)		
Mesozoic.	Cretaceous.		Chico.	(?)	(?)
			Unconformity		
			Horsetown.		
			Unconformity		
			Knoxville.		
			Unconformity		
	Jurassic (?).		Franciscan.	Franciscan? (fide Whitney).	
			Unconformity		Unconformity
			Granite, schist, etc.		Granite, gneiss, etc.

TOPATOPA FORMATION.

Name.—The name Topatopa was given by Eldridge[a] to a formation of conglomerate, sandstone, quartzite, and shale exposed in the Topatopa Range north of the Santa Clara Valley, Ventura County, about 30 miles east of the Summerland district. As the deposits thus described are directly traceable into a similar series occurring in the Santa Ynez Range in this district, Eldridge's name has been employed to designate the latter formation.

Lithologic character.—Four zones, the upper three each approximately 2,500 feet in thickness, the lowest at least 1,200 feet thick, are recognizable in the Topatopa formation north of Summerland. The lowest zone is predominatingly dark-drab to greenish shale, generally thin bedded, with varying amounts of yellowish, grayish, and drab interbedded sandstone. The sandstone layers range in thickness from a fraction of an inch to several feet and in grain from fine to pebbly. The sand grains are largely quartzitic and the pebbles granitic, as they are also throughout the remainder of this and the succeeding (Sespe) formation. The shale contains some carbonaceous material, scattered fish integuments, and what are supposed to be ostracods.

The second zone is similar to the first except that in the second the sandstones are relatively much more important than the shales, some of the sandstone beds approaching 25 or 50 feet in thickness.

Above this sandstone zone is a very prominent band of dark-gray to greenish thin-bedded shale, which, owing to its soft composition, forms a swale in all the ridges running down from the crest of the range for many miles along its front. Some decidedly calcareous beds are associated with the shale, as are also some thin beds of sandy material. Many tar springs occur in the shale about the region of Toro and Oil canyons, and in it the wells of the Occidental Oil Company, in the latter canyon, described on page 55, were drilled.

The uppermost zone of the Topatopa consists largely of hard sandstone and conglomerate, with here and there more or less prominent belts of gray shale, and is sparingly fossiliferous throughout. The sandstone beds vary in thickness from a few inches to 50 or 60 feet, the thicker beds appearing near the stratigraphic top of the series, toward the foot of the steep slopes. A row of prominent knobs on the transverse ridges of the south face of the range (immediately in front of the swales described as being weathered out of the shale) are determined by the position of the hard sandstone beds at the base of this uppermost member of the Topatopa.

Some very good building stone is obtained from the Topatopa formation near the base of the mountains and also from bowlders of the same rock found on the detrital slopes south of them.

[a] Bull. U. S. Geol. Survey No. 309, 1907, p. 5.

Age and fossils.—The age of the Topatopa formation is Eocene, as shown by characteristic fossils found in it both in the type locality and in the region of Santa Barbara. Many fossiliferous layers occur throughout the upper sandstone member of the formation, but most of these contain only poorly preserved oysters. However, at one locality on the La Cumbre trail, on the ridge between Rattlesnake and Sycamore canyons, north of Santa Barbara, the writer collected the following fauna from the sandstone about 1,000 feet stratigraphically below the top of the Topatopa formation:

Eocene fossils from the Topatopa formation on the ridge between Rattlesnake and Sycamore canyons, Santa Barbara, Cal.

Cardium brewerii Gabb (Young) (Pl. IX, fig. 5).
Galerus excentricus Gabb (Pl. X, figs. 3a and 3b).
Leda gabbi Conrad (Pl. X, fig. 1).
Mactra near ashburneri Gabb (Pl. X, fig. 6).
Meretrix uvasana Conrad (Pl. IX, fig. 1; Pl. X, fig. 5).
Meretrix sp. indet.
Modiolus ornatus Gabb (Pl. X, fig. 4).
Ostrea idriaensis Gabb (Pl. IX, fig. 2).
Phacoides cretacea Gabb (Pl. IX, fig. 4).
Phacoides sp. (small, gibbous).
Spirocrypta pileum Gabb (Pl. X, figs. 8, 9a, and 9b).
Thracia (?) sp.
Turritella uvasana Conrad (Pl. X, fig. 7).

Distribution and structure.—The Topatopa formation occupies the whole front of the Santa Ynez Mountains from the region of the Ojai Valley at least as far west as Santa Barbara. In the region north of the Ojai Valley it forms the heart of a great anticline overturned toward the south; farther west, in the region of Chismahoo Mountain, the same anticline is normal; but still farther west, in the region back of Summerland and Carpinteria, the anticline is again overturned toward the south and the beds, from the foot to the summit of the range, all dip northward at angles varying from 40° to 90°, the youngest apparently being at the bottom of the series. Northeast of Summerland and north of Carpinteria a long, narrow block of uppermost Topatopa sandstone and shale, dipping steeply to the south, is thrown up on the south side of a prominent east-west fault.

Evidences of petroleum.—The Topatopa is petroliferous in the type locality in the Sespe region, and, as previously mentioned, tar springs are found in the upper shale member of the formation in Oil and Toro canyons. Furthermore, wells put down in the vicinity of these last-mentioned springs have yielded some 14° to 17° oil. Besides these occurrences, oil seepages are said to occur in the Topatopa brown sandstones and shales in the canyon of Arroyo Parida, northeast of Serena, and at several other localities in the same formation along the south face of the Santa Ynez Range. Taken as a whole, however, the structure of the formation in the Summerland district offers only moderate inducements for prospecting with the drill.

Water from the Topatopa formation.—Hot springs emanate from the rocks of the Topatopa formation in Hot Spring Canyon, 4 miles

northeast of Santa Barbara. According to Whitney,[a] the waters from these springs are highly charged with sulphur, and had in March, 1861, temperatures ranging from 112° to 118° F., the larger ones being usually the warmer.

The following is an analysis[b] of water from the tunnel or one of the wells of the Occidental Oil Company in Toro Canyon, which are sunk in the upper Topatopa shale zone:

Analysis of water from Occidental wells, Toro Canyon, 3 miles northeast of Summerland.[c]

	Parts per million.
Silica	29.344
Oxide of iron and alumina	2.787
Carbonate of lime	105.045
Carbonate of magnesia	74.812
Sodium and potassium sulphate	17.186
Sodium and potassium chloride	22.572
Sodium and potassium carbonate	57.832
Oil and organic matter	Trace.
	309.578

This water passed directly into a boiler without going through the heater would scale and cause some pitting, but in the heater the lime and magnesium are largely precipitated.

SESPE FORMATION.

Name.—The name "Sespe brownstone formation" was first used by Watts[d] in describing the peculiar reddish-brown sandstone series found in the region of the Sespe Canyon, north of Fillmore, Ventura County. Later the name was used by Eldridge[e] for the characteristic reddish formation of which the Sespe brownstone is a part. The name is used in this report to designate the reddish formation which occurs along the flanks of the Santa Ynez Range north of Santa Barbara and Summerland, and which is directly traceable into Eldridge's areas in Ventura County.

Lithologic character.—Two general divisions are recognizable in the Sespe formation—a sandy basal portion about 1,900 feet thick and a shaly upper portion about 2,400 feet thick. The middle of the formation is of a decidedly characteristic reddish color, but this fades out gradually both toward the bottom and toward the top. The lowest zone in the Sespe is about 300 feet of heavy-bedded coarse

[a] Geol. Survey California, Geology, vol. 1, 1865, p. 128.

[b] This analysis was found in Mr. Eldridge's notebook, accompanied by the following note: "Given me by Mr. Rust, of the Seaside Oil Company. Analysis by Dearborn Drug and Chemical Company, Chicago, September 6, 1900."

[c] Expressed by analyst in grains per gallon; recomputed to parts per million at United States Geological Survey.

[d] Bull. California State Mining Bureau No. 11, 1897, p. 25.

[e] Bull. U. S. Geol. Survey No. 309, 1907, p. 7.

pinkish sandstone with a few conglomerate layers. Above this is 340 feet of heavy-bedded, coarse yellowish granitic sandstone; then 330 feet of heavy-bedded granitic sandstone, locally pinkish in color; and, finally, 950 feet of medium-bedded, characteristic reddish-brown siliceous conglomerate and coarse sandstone, with minor amounts of clayey shale. The upper horizon has 1,815 feet of thin to thick beds of characteristic brownish-red clayey shale with minor amounts of sandstone and conglomerate, the whole becoming lighter colored toward the top, and about 575 feet of light-brown shale, with white to pinkish calcareous concretions, these latter beds being transitional into the Vaqueros shale above.

Some of the harder Sespe conglomerate makes excellent road material and is quarried extensively for this purpose at different points along the base of the mountains. Good building stone could doubtless be obtained from the formation at certain localities, although at present the only place where the rock is quarried is in Sespe Canyon, Ventura County.

Age.—No fossils have been found in the Sespe formation in the Summerland district. Watts and Eldridge, from their studies in Ventura County, are of the opinion that the Sespe is largely Eocene, although their evidence for this belief is not conclusive. It is quite probable that the base of the formation is Eocene, as characteristic Eocene forms have been found in the top beds of the Topatopa formation, which conformably underlies the Sespe. It seems possible that at least a part of the Sespe is Oligocene, for it grades at the top into beds which at several localities are known to contain lower Miocene fossils.

Distribution and structure.—The Sespe formation is exposed almost continuously from the type locality in Sespe Canyon at least as far west as Santa Barbara, and probably much farther. What is thought to be an outcrop of the Sespe is also exposed in the core of the anticline of Vaqueros sandstone south of Santa Ynez, nearly 40 miles west of Santa Barbara. In the Summerland district the Sespe lies stratigraphically above the Topatopa, with which it is conformable, forming a band averaging about a mile in width immediately south of that formation at the base of the Santa Ynez Range. North of the eastern part of the city of Santa Barbara the band of Sespe deposits is affected by the overturn and dips northward at steep angles under the older Topatopa beds; north and northwest of the Mission the beds occupy their normal relation to the Topatopa and dip toward the south. The belt of Sespe at the base of the range northeast of Summerland lies in a syncline overturned toward the south; farther east, however, this syncline rights itself and extends as a broad trough as far east as the Ojai Valley.

Another band of the Sespe occupies the flanks of the ridge between Toro Canyon and the east end of the area shown on the map; it also extends westward from Toro Canyon, forming a large part of the group of hills immediately northeast of Summerland. In this band the Sespe dips south at a steep angle, its base being determined by exposures of the underlying Topatopa, while its upper beds are for the most part hidden under the Pleistocene deposits of the lowland. A little isolated outcrop of Sespe forming the two knolls in the bend of Ficay Creek, 1½ miles northeast of Summerland, is a part of the uppermost light-brownish shale of the formation. As this exposure lies in the direct line of strike of the basal sandstone beds of the Sespe outcrop in the ridge immediately to the southeast, it is very evidently separated from the beds in the ridge by a profound fault, with a downthrow on the north.

Evidences of petroleum.—No evidences of petroleum were found by the writer in the Sespe beds in the Summerland district. However, the same formation is petroliferous in the region of Sespe and Sisar canyons, farther east, and it is said that certain indications of oil have been found by others in the Sespe northeast of Summerland. The well of the Pinal Oil Company, on the west side of Arroyo Parida, starts down in the basal sandstone of the Sespe, but it is thought that this well was located with the intention of tapping the shales at the top of the Topatopa formation, which lies just below, rather than with the idea of obtaining oil from the Sespe.

VAQUEROS FORMATION.

Name and correlation.—The name Vaqueros was proposed by Homer Hamlin for a characteristic sandstone formation underlying the Monterey shale in Los Vaqueros Valley, Monterey County, and was first used by H. W. Fairbanks[a] for the lower Miocene of the San Luis quadrangle. Owing to its characteristic fauna, the formation has been recognized over much of the Coast Range belt. Although what is called the Vaqueros formation in the Summerland district contains no characteristic fossils, its stratigraphic position and lithologic similarity to certain characteristically fossiliferous beds in the Ojai Valley to the east leave no doubt in the mind of the writer as to its correct correlation.

Lithologic character.—The basal portion of the Vaqueros consists of several beds of fine to coarse, more or less arkose, light-brownish sandstone, interbedded with minor quantities of dark earthy to sandy shale, about 785 feet in all. This sandy zone is apparently somewhat more resistant to weathering than the shale above, as is indicated by its presence in the row of knolls one-half mile northeast of Summerland. Above the sandy zone and grading into the overlying Monte-

[a] Geologic Atlas U. S., folio 101, U. S. Geol. Survey, 1904, p. 3.

rey shale is about 1,650 feet of grayish clayey shale, with many layers of gray to yellow calcareous shale or calcareous concretions; the shale is darker colored toward the top and apparently less sandy than lower down. The whole shaly portion of the formation weathers into black adobe soil, in which the hard lime concretions are abundant; the sandy portion of the Vaqueros produces a lighter colored soil than the shale.

The Vaqueros in this district contains little of the coarse sandstone which is so characteristic of the formation in the region at the west end of the Santa Ynez Range. In this respect it is like the Vaqueros of the Sespe and Ojai regions, which is made up largely of shale.

No indications of petroleum were noticed by the writer in any of the exposures of the Vaqueros in the Summerland district.

Distribution and structure.—The Vaqueros fine sandstones and shales lie conformably above the light-colored shale of the Sespe formation in the region north of Summerland and also north and northwest of Santa Barbara. In the Summerland area the beds vary in dip from 70° to 90° NW., with a strike of northwest-southeast. In the region north of Santa Barbara the same beds appear to be overturned and dip steeply northward, with a west-northwest strike parallel to the major structural features of the range.

MONTEREY SHALE.

Name.—In 1855 William P. Blake[a] described the diatomaceous shales in the vicinity of Monterey and applied to them the name that has been accepted ever since by west-coast geologists to designate the characteristic shale formation of the middle Miocene, which has so widespread a distribution in the Coast Ranges of California.

Lithologic character.—As in many portions of the Coast Ranges, the Monterey in the Summerland district is in general distinguished by its diatomaceous character. Unusually pure diatomaceous earth, or tripoli, as it is sometimes called, is found in the areas of Monterey adjacent to Sycamore Canyon and southwest of Montecito. These deposits have been the subject of a special paper by Finch. (See p. 13.) Similar deposits in the northern part of Santa Barbara County are described by the writer and Robert Anderson in "Contributions to Economic Geology for 1906."[b] This diatomaceous earth usually contains from 70 to 85 per cent of silica, is white to light-yellowish in color, very light in weight, and fairly resistant to weathering. The siliceous shells of the individual diatoms are usually distinguishable under a lens in most hand specimens of this material.

In the region of the Carpinteria asphalt quarry the shales are highly bituminous, and have assumed contrasting alternations of

[a] Proc. Acad. Nat. Sci., Philadelphia, vol. 7, 1855, pp. 328-331.
[b] Bull. U. S. Geol. Survey No. 315, 1907, pp. 438-447.

black, brown, and white, which are rendered more conspicuous by the action of the waves. Along the railroad immediately east of the area shown on the map the shale is interbedded at rare intervals by 4-inch to 24-inch, fine, brownish, more or less bituminous sandstone layers.

Volcanic ash occurs at two horizons toward the base of the Monterey northwest of Summerland, as shown on the map (Pl. I, p. 18). The lower deposit is about 125 feet and the upper about 75 feet in thickness. The lower is slightly coarser grained than the upper. The ash is white and very gritty, and consists largely of angular grains of quartz and lath-shaped feldspar crystals, some more than 2 or 3 mm. in length.

The Monterey shale becomes strongly porcelaneous in the area northwest of the Santa Barbara Mission, and in some places even approaches a flint in texture. The beds here are harder than any others occurring in this formation in the district.

The following log shows the character of the Monterey in the hills immediately north of Summerland:

Log of well in Monterey formation one-third mile north of Summerland Station.

	Thickness.	Depth.		Thickness.	Depth.
	Feet.	*Feet.*		*Feet.*	*Feet.*
White and blue clay	50	50	Blue shale	80	200
White shale	50	100	Sandstone (probably volcanic-ash bed, steeply tilted); specks of oil	300	500
Hard "shell" on incline	1	101			
Broken shale with gas	1½	102½			
Chocolate-colored shale	17½	120			

Salt water below sea level in this well.

Age and fossils.--Recognizable marine molluscan fossils were found in the Monterey at only one locality in the district. This was on the south face of the 675-foot hill just east of Diablo Canyon and a little more than a mile northwest of the Mission. Here the semiporcelaneous shale and an interbedded fine sandstone layer yielded the following fossils: *Arca* sp. (small), *Pecten peckhami* Gabb (abundant and beautifully preserved as casts; Pl. X, fig. 10), and *Phacoides* sp. (small, gibbous).

Distribution and structure.—The Monterey formation occupies a belt lying conformably above the Vaqueros in front of the whole length of the Santa Ynez Range in the Summerland district. Over much of the territory the shale is covered by the Pleistocene deposits, but at certain localities erosion has stripped the beds clear of their overlying mantle and they are shown in all their complexity of structure. Beautiful sections are disclosed in the sea cliff for many miles southeast of the mouth of Carpinteria Creek (see Pl. III, *A*), while west of Punta del Castillo and Santa Barbara Point there are other

A. BEACH NEAR CARPINTERIA ASPHALT MINE, SHOWING UPTURNED AND CONTORTED MONTEREY SHALE.

The exuding tar cements seaweed, pebbles, and rocks into a firm conglomerate. Eluff in rear is composed of sands heavily impregnated with asphaltum.

B. A TAR VOLCANO IN THE CARPINTERIA ASPHALT MINE.

Showing how oil exudes from joint cracks in the upturned Monterey shale forming the floor of mine.

excellent exposures. North of Summerland and north of Santa Barbara are isolated patches of this formation.

In the western part of the district the shale dips northward at angles of 40° to 90°, being affected by the overturn which controls the position of the beds in the Santa Ynez Range; north of Summerland it dips steeply to the southwest, while at the asphalt quarry at Carpinteria it stands exactly vertical, changing, however, to a northeasterly dip farther east along the coast. Toward the east edge of the area mapped the shale is folded into an anticline striking a little north of west, with dips of 30° on its northeast flank and 45° on its southwest flank, near the axis. The shale is much contorted and fractured locally, especially in the region along the coast half a mile east of Carpinteria. The well of the Columbia Oil and Asphalt Company, 1 mile southwest of Carpinteria, is located near the axis of this anticline.

Evidences of petroleum.—The Monterey shale is probably the ultimate source of most of the oil occurring within this and most of the other productive oil fields of the Coast Ranges. The petroleum is thought to be the product of a slow and complicated process of metamorphism and distillation affecting the hydrocarbon material in the diatoms and other organic remains which play so prominent a rôle in the formation of these shales. This subject is more fully discussed in Bulletin No. 322 of the United States Geological Survey.

In the vicinity of the Carpinteria asphalt mine and to the southeast along the shore for about a mile the shale is very petroliferous, tar oozing from the joint cracks at many places. This substance not only forms black coatings over the exposures on the beach, but cements sea weed, shells, and pebbles into a firm conglomerate which forms a layer over the rocks near the water. (See Pl. III, *A*.) Deposits of asphaltum are formed from the oil or tar which exudes from the shales and penetrates the overlying Pleistocene sands. Pl. III, *B*, shows a characteristic seepage of oil from the Monterey shale forming the floor of the Carpinteria asphalt mine. Wells drilled in the shales in this vicinity also yield small amounts of heavy oil. This occurrence of petroleum in the shale is associated with a zone of fracture and a fold parallel to this zone, affecting the Monterey along this part of the coast.

At many places west of Santa Barbara as far as Gaviota the Monterey shales exude oil and tar, some localities furnishing asphalt in commercial quantities.[a] Wells in the Summerland field which penetrate the Monterey usually strike small quantities of gas, but no oil worthy of mention.

With the exception of the exposures along the coast the surface evidences of petroleum in the Monterey are not noteworthy. Certain

[a] See Mem. California Acad. Sci., vol. 3, 1903, pl. 32, fig. a.

shales exposed in the Arroyo de las Ortegas, northwest of Summerland, show some signs of petroleum, as do the shales in one or two other exposures farther west, but these are of little importance.

FERNANDO FORMATION.

Name.—The name "Fernando" was used on a manuscript map by Homer Hamlin several years ago to specify a certain formation containing Pliocene fossils and unconformably overlying the Monterey shale in the San Fernando Valley, Los Angeles County. It has since been used by Eldridge and Arnold[a] to designate the same formation throughout the oil fields of Ventura, Los Angeles, and Orange counties, and still more recently by Arnold and Anderson[b] for an equivalent formation in northern Santa Barbara County.

Lithologic character in the Summerland area.—The Fernando, in the region east of Santa Barbara, consists of clay and clayey shale, sandstone, and conglomerate. The last two contain oil toward the base of the formation over much of the territory south and southeast of Summerland.

Clayey shale appears to comprise something like 400 feet of strata at the base of the Fernando in the Summerland region. Some exposures of this shale occur in a cut on the north side of the county road in the eastern part of the town, and also at two places along the beach between the easternmost Duquesne wharf and Loon Point. The shale is rather soft, gray to brown in color on fresh surfaces, but rusty in the joint cracks, of which there are many cutting the rock. Gypsum occurs in numerous small veins in the outcrop on the county road, and gypsum and sulphur both are abundant in the outcrops along the beach. Sandy clay shale and bluish and grayish clay are also interbedded with the sandstones and conglomerates, which overlie the basal shale. The clays usually slack on exposure. The gypsiferous sandy clay shale exposed in the bluff opposite the cemetery 1 mile north of Montecito Landing probably represents a zone higher up in the formation than the similar beds at Summerland.

Sandstone and conglomerate with some interbedded clays make up the upper portion of the Fernando, the coarse sediments being composed largely of waterworn Eocene sandstone with scattered pebbles of quartzite and other hard rocks. (See Pl. IV.) From one-eighth to one-half mile west of the westernmost Summerland wells the formation is very conglomeratic, and contains bowlders up to 2 feet in diameter, the average, however, being under 6 inches. The pebbly bodies are incoherent and form strata and great irregular masses. Fine yellowish to pinkish sands and one or two streaks of dark-gray clay are interbedded with the conglomerate at this locality. At the

[a] Bull. U. S. Geol. Survey No. 309, 1907, p. 22.
[b] Bull. U. S. Geol. Survey No. 317, 1907, p. 19; and No. 322, 1907.

UNCONFORMITY NEAR NORTH STAR WHARF. LOOKING WEST.

Pleistocene deposits resting : nearly vertical oil-bearing Fernando sandstone and conglomerate.

west end of the field the beds are lower in the formation than those just described, but closely resemble them. Larger bowlders, some up to 4 feet in diameter, occur in these lower beds, and interstratified blue clays become more abundant as the base of the formation is approached. Evidences of petroleum are first encountered in that part of the formation exposed in the railroad cut near the westernmost wells, in the sandy and conglomeratic layers, and from this horizon down (stratigraphically) for over 200 feet the beds are more or less petroliferous. The oil-bearing strata are also encountered near Loon Point, where they consist of yellowish to reddish sandstone and conglomerate. Similar rocks outcrop in the bluffs 1 mile north of Montecito Landing.

Lithologic character in the Santa Barbara area.—The Fernando formation in Packards Hill southwest of Santa Barbara, consists of fossiliferous sandy marl, sandstone, and sandy shale dipping slightly west of south at angles varying from 15 to 45 degrees. In the bluffs at the eastern end of the hill, near the bath house, the formation consists largely of bryozoan marl and sandstone, certain layers being exceedingly fossiliferous. The more fossiliferous layers are much the harder, and form protruding shelves along the face of the bluff.[a]

Age and fossils.—No fossils have been found in the Fernando formation in any of the outcrops at Summerland, Loon Point, or Montecito, but in the area southwest of Santa Barbara an abundant marine fauna representing two horizons is present.

The fossiliferous beds are certainly of marine origin, and are known to represent horizons in the body of this formation; the beds in the Summerland areas are of unknown origin, but are undoubtedly at the base of the Fernando and rest on beds of middle Miocene (Monterey) age. The fossil-bearing strata are certainly Pliocene, and may extend over into the Pleistocene, so that it is probable that the lower or unfossiliferous part of the formation is either lower Pliocene or upper Miocene.

[a] Mem. California Acad. Sci., vol. 3, 1903, pl. 31, fig. b.

The following species have been found in the marine beds southwest of Santa Barbara:

Fossils collected from the Fernando formation at Santa Barbara.[a]

	Bath-house Beach.	Pack-ards Hill.
Acmæa insessa Hinds	×	....
Admete gracilior Carpenter	×	....
Amphissa corrugata Reeve (Pl. XI, fig. 7)	×	....
Balanus concavus Bronn	....	×
Bela fidicula Gould	×	....
Bittium barbarensis Bartsch (Pl. XI, fig. 15)	×	....
Bittium catalinensis Bartsch (Pl. XI, fig. 13)	×	....
Bryozoa sp. (?) (See Pl. XVII)	×	×
Cardium corbis Martyn	×	....
Calliostoma gemmulatum Carpenter	....	×
Chrysodomus tabulatus Baird	×	....
Clathurella conradiana Gabb (Pl. XI, fig. 9)	×	×
Columbella (Astyris) gausapata Gould	×	....
Columbella (Astyris) gausapata var. carinata Hinds	×	....
Columbella (Astyris) tuberosa Carpenter (Pl. XI, fig. 10)	×	....
Crepidula adunca Sowerby	×	....
Crepidula navicelloides Nuttall	×	....
Crepidula princeps Conrad (Pl. XIII, figs. 1a, 1b, 1c)	....	×
Cythara branneri Arnold	×	....
Diastoma sp. (?)	×	....
Fusus robustus Trask	×	....
Galerus mammilaris Broderip (Pl. XI, fig. 14)	×	×
Glottidia albida Hinds	....	×
Lacuna compacta Carpenter (Pl. XI, fig. 2)	×	....
Laqueus jeffreysi (?) Dall	....	×
Leptothrya bacula Carpenter (Pl. XI, fig. 3)	×	....
Leptothyra paucicostata Dall (Pl. XIII, fig. 3)	×	....
Macoma sp. (?)	×	....
Mangilia angulata Carpenter	×	....
Mangilia interfossa var. pedroana Arnold	×	....
Mangilia tabulata Carpenter (Pl. XI, fig. 4)	×	....
Margarita pupilla Gould	×	....
Mercenaria perlaminosa Conrad (Pl. XV, figs. 1a, 1b, 1c)	×	×
Mitramorpha filosa Carpenter var. barbarensis Arnold (Pl. XI, fig. 1)	×	....
Modiolus fornicatus Carpenter	×	....
Nassa mendica Gould	×	....
Nassa perpinguis Hinds (Pl. XI, fig. 8)	×	....
Natica clausa Broderip and Sowerby (Pl. XVI, fig. 2)	×	×
Ocinebra barbarensis Gabb	×	....
Ocinebra lurida Middendorf (Pl. XI, fig. 11)	×	....
Ocinebra lurida var. aspera Baird	×	....
Ocinebra perita Hinds	×	....
Odostomia nuciformis var. avellana Carpenter	×	....
Odostomia gouldii Carpenter	×	....
Olivella biplicata Sowerby	×	....
Panopea generosa Gould	....	×
Pecten (Pecten) bellus Conrad (Pl. XV, figs. 1a, 1b)	....	×
Pecten (Patinopecten) caurinus Gould (Pl. XVI, figs. 1a, 1b)	×	×
Pecten (Chlamys) hastatus Sowerby (Pl. XIV, figs. 6a, 6b)	×	×
Pecten (Chlamys) hastatus Sowerby var. strategus Dall	×	×
Pecten (Chlamys) jordani Arnold (Pl. XIV, figs. 5a, 5b)	....	×
Pecten (Chlamys) opuntia Dall (Pl. XIV, figs. 3, 4)	....	×
Phacoides annulatus Reeve	×	×
Phacoides californica Conrad	×	....
Pododesmus macroschisma Deshayes	×	....
Protocardia centifilosa Carpenter	×	×
Psephidia barbarensis Arnold (Pl. XII, fig. 3)	×	×
Puncturella cuculata Gould	....	×
Puncturella delosi Arnold (Pl. XI, figs. 5a, 5b)	×	....
Semele pulchra Sowerby var. montereyi Arnold (Pl. XIV, fig. 1)	×	....
Strongylocentrotus purpuratus Stimson	×	....
Terebratalia hemphilli Dall (Pl. XII, figs. 4a, 4b)	....	×
Tornatina culcitella Gould (Pl. XI, fig. 6)	×	....
Trophon (Boreotrophon) gracilis Perry	×	....
Trophon (Boreotrophon) orpheus var. præcursor Arnold	×	....
Trophon (Boreotrophon) stuarti Smith (Pl. XI, fig. 12)	×	....
Turbonilla tridentata Carpenter	×	....
Venericardia monilicosta Gabb (Pl. XIV, fig. 2)	×	×
Venericardia yatesi Arnold (Pl. XII, figs. 2a, 2b)	×	×

[a] Mem. California Acad. Sci., vol. 3, 1903, p. 52.

Distribution and structure.—Only a very small percentage of the area discussed in this report is occupied by the Fernando, but as it is the

formation that contains the productive oil sands of the Summerland field it is one of the most important. The contacts of this formation with those adjacent, as shown on the map, are at nearly every place arbitrarily determined, owing to the soft composition of both the Fernando and the Monterey and the similarity of the overlying Pleistocene deposits to the Fernando. Three general areas are shown on the map. That at Summerland borders the coast and is affected by one or more irregular, undulating anticlines which parallel in a general way the other structural lines of the region. Another small area, also lying in an anticlinal position, is exposed in the bluff 1 mile west of Montecito Landing. The third and most important district occupies Packards Hill, southwest of Santa Barbara, where the formation lies in a great southwestward-dipping monocline at least as far as the middle of the area. This outcrop was not studied in detail, so that its relations to the Monterey shale, which borders it along the coast on the southwest, are not known.

Evidences of petroleum.—Surface indications of petroleum, in the form of chocolate-colored bituminous sandstone, appear at Loon Point at intervals for one-half mile to the west, and also along the cliffs at the west end of the field. The uppermost bed that shows signs of impregnation occurs in the railroad cut a short distance west of the westernmost Southern Pacific well on the bluff. (See Pl. VI, p. 36.) The strike of this bed and its associated conglomerates (which are locally called "the reef") would carry it to the southeast, toward the end of the Southern Pacific wharf. No productive wells have been found southwest of the submarine outcrop of this reef bed. Although similar to the Loon Point Fernando beds, and occupying structurally an apparently analogous position, the sandstone and conglomerate exposed in the anticline 1 mile west of Montecito Landing yield no indications of oil. Neither does the marine Fernando west and southwest of Santa Barbara. A discussion of the productive oil sands which occur in the Fernando is given under the heading "De-description of the wells" (pp. 39–49).

PLEISTOCENE DEPOSITS.

Lithologic character.—The Pleistocene deposits in the Summerland district are of several kinds and include detrital accumulations, marine beds, and certain sandy clays of uncertain origin. The detrital deposits are incoherent and consist of poorly assorted material, ranging in texture from fine sand to great bowlders of the Eocene sandstone 10 or 12 feet in diameter. This material has been brought down from the mountains by the streams during periods of flood and spread out on the slopes at the mouths of the steep canyons. The presence of the huge bowlders on the slopes of Mission Ridge and at other places at

least a mile from the mouth of the nearest canyon implies a tremendous carrying power for the depositing stream.

The beds exposed in the bluffs along the shore extend inland for an indefinite distance, probably as far as the inner margins of most of the terraces, and are composed of gravel and sand with which finer sediments are locally interbedded. (See fig. 2; also more particularly Pl. II, *B*, and Pl. IV, p. 30.) Extreme variation takes place abruptly not only in the vertical succession, but also in individual layers, which at many places vary conspicuously in thickness and in composition within short distances, sand replacing gravel, and clay locally taking the place of sand, and vice versa. Bituminous sands and gravels occur at the base of the Pleistocene in certain areas, such as at Summerland and Carpinteria, and flowing water is struck at the same horizon in the region of Carpinteria Creek. Oil and water are encountered in wells near Serena at depths of 25 to 100 feet in what is supposed to be the basal Pleistocene gravel.

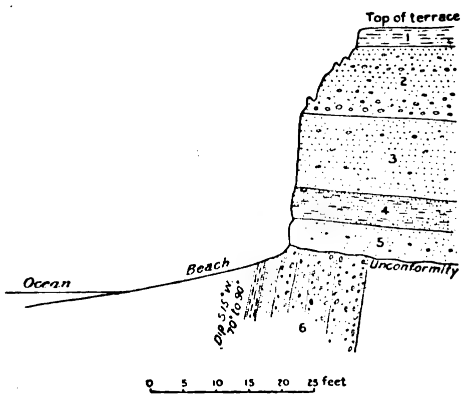


FIG. 2.—Detailed section of bluff near North Star wharf. Pleistocene: 1, Dark-brown soil; 2, drab clayey sand and conglomerate; 3, yellow quartzose and feldspathic sand, with distributed pebbles; 4, fossiliferous fine compact sand and clay; 5, brown bituminous sand, some sandstone pebbles. Pliocene: 6, Gray shale, sandstone, and conglomerate.

The basal beds of the marine Pleistocene are fossiliferous at Summerland, at Carpinteria, and north of Montecito Landing, the latter locality yielding a good fauna from a bed 1 to 2 feet thick. The species are those still found living in adjacent waters. In the Carpinteria asphalt mine the two rock-boring mollusks *Pholadidea penita* Conrad and *Petricola carditoides* Conrad are particularly abundant in the floor of the mine, which was once the top of the Pleistocene terrace.

In the lowlands along the Santa Barbara, Montecito, and Summerland roads occurs a formation of sandy clays, blue to yellowish in fresh cuts, that is very tenacious and more or less porous from the apparent rotting of contained vegetable matter, etc., and therefore resembles loess. The beds carry small pebbles, which are derived from the adjoining mountain slopes. The formation lies flat and is apparently undisturbed. It is thought possible that these beds are of fresh or brackish water origin, although no fossils or other direct evidence have been found in support of this theory.

Distribution.—The Pleistocene deposits cover a large part of the mapped area, hiding the older formations over most of the lowlands south of the main range. The detrital deposits are probably the most important and cover the slopes contiguous to the base of the mountains; those of marine origin skirt the coast and cover the old terraces; while the clays and fine sands, which are believed to be of fresh-water or possibly brakish-water origin, lie in the region between Santa Barbara and Summerland.

The Pleistocene beds vary materially in thickness from point to point, at one place forming a thin veneer over the older rocks and at another, as in the area east of Carpinteria Creek and for a mile from the ocean, being about 150 feet thick. This last-described area occupies an old basin or valley, probably the abandoned channel of Rincon Creek. In the northern part of the Summerland field the Pleistocene is over 50 feet thick.

Evidences of petroleum.—Bituminous sand and gravel, deriving their hydrocarbon contents by infiltration from the underlying formations, are found in the Pleistocene at many localities along the coast from Goleta to Rincon Creek. In some places these have been worked for the asphalt; in others the degree of impregnation of the sands has been so slight as to preclude their profitable exploitation. The asphalt deposits have been described by Eldridge[a] and others, and the Summerland occurrences only will be mentioned here.

The basal Pleistocene layer in the bluff opposite the northern part of the town consists of chocolate-colored to brown bituminous sand containing a few sandstone pebbles. The bed varies in thickness from 4 or 5 feet to more than 10 feet, thickening toward the west but finally disappearing opposite the western wells of the field. Here it abuts against the steeply dipping Fernando conglomerates of Ortega Hill, which protrude over it, thus implying its deposition at this point in a wave-cut cave. The beds dip toward the northeast at angles up to 8° or 10°, and for this reason have been erroneously correlated by some operators with the Fernando beds, which dip steeply southwestward (see fig. 2, p. 34). The bituminous sand is so heavily charged in certain places in the Summerland field that some fresh exposures of it are said to have yielded considerable oil. Weathered surfaces, by a loss of the more volatile constituent of the oil, dry out and seal up the inner portions.

An oil spring is mentioned by Watts[b] as being exposed at low tide on the seashore one-fourth of a mile southwest of Martin's ranch, Serena.

[a] See reference under "Previous knowledge of the region," pp. 15-16.
[b] Bull. California State Mining Bureau No. 11, 1897, p. 52.

STRUCTURE.

GENERAL STRUCTURE OF THE DISTRICT.

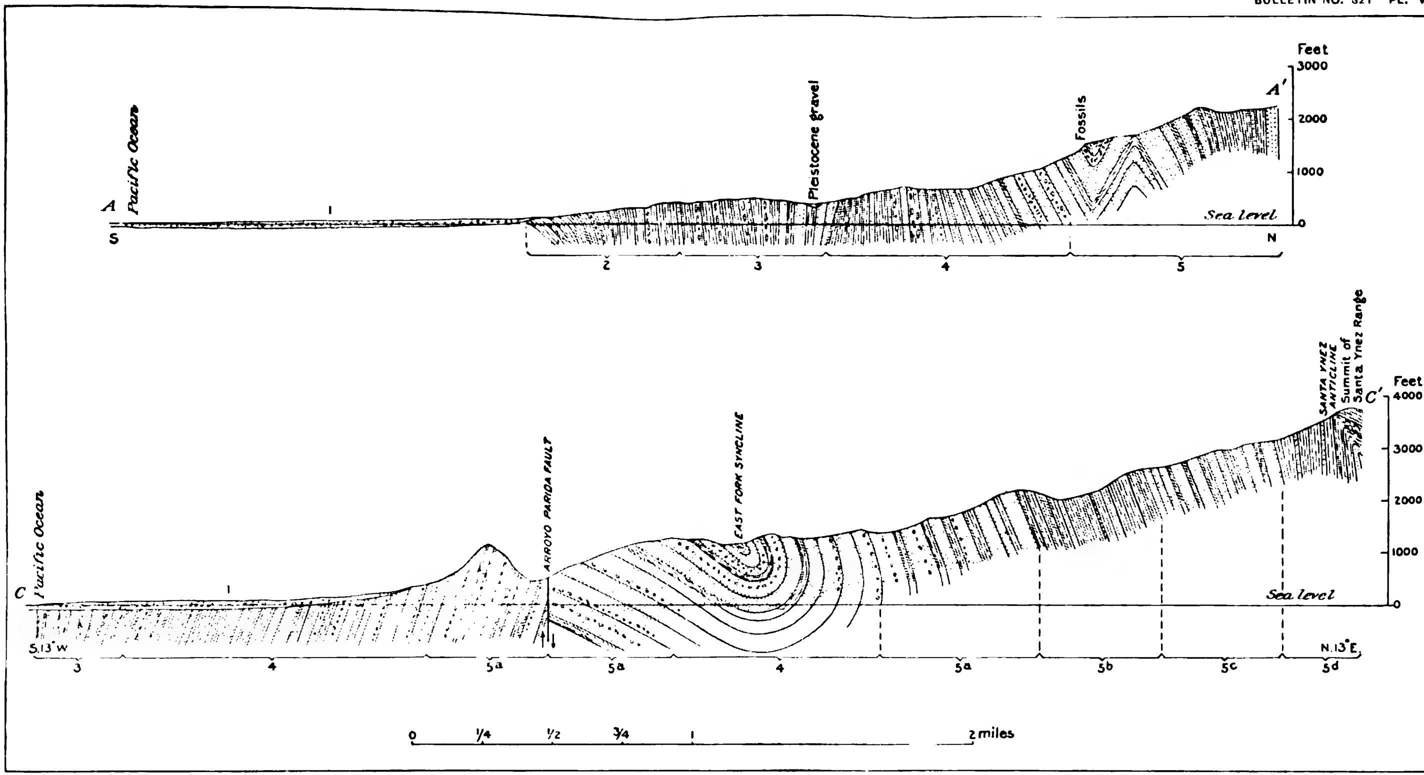
The great overturned anticline previously referred to as elevating the main portion of the Santa Ynez Range is the dominant structural feature of the region, although there are in addition to this one an important faulted anticline northeast of Summerland, some complex folds in the range north of Santa Barbara, and several other minor flexures and zones of disturbance near the ocean. The reader's attention is called to the sections (Pls. V, VII, *A*, and VIII) and the contour map (Pl. VI), as elucidating the statements made in the following paragraphs:

SANTA YNEZ RANGE ANTICLINE.

The great anticline of the Santa Ynez Range is believed to be the westward continuation of the overturned anticline which affects the rocks of the Topatopa Range north of the Ojai Valley 15 miles east of the Summerland district. Throughout its extent it trends practically in an east-west direction. From some undetermined point west of the Ojai Valley westward nearly to the intersection of Steer and Eldorado creeks, something over a mile east of the east edge of the area covered by the map (Pl. I, p. 18), the anticline is normal and its south flank dips southward at angles ranging from 30° to 90°. From the intersection of the creeks just mentioned westward at least as far as Montecito and probably farther the anticline is again overturned, the south flank of the fold dipping to the north at angles varying from 40° to 90° (see section *C*-*C*″, Pl. V). In the region west of Montecito Peak the structure becomes more or less complex, although it is certain that the overturn, so far as it affects the Sespe and younger formations, extends practically to the west edge of the area mapped (see section *A*-*A*′, Pl. V). In the region of Sycamore Canyon the Monterey (middle Miocene) shale has been so far overturned as to dip 40° or even less toward the north. These dips in the shale, however, may possibly be due to local crumpling.

ARROYO PARIDA ANTICLINE AND FAULT.

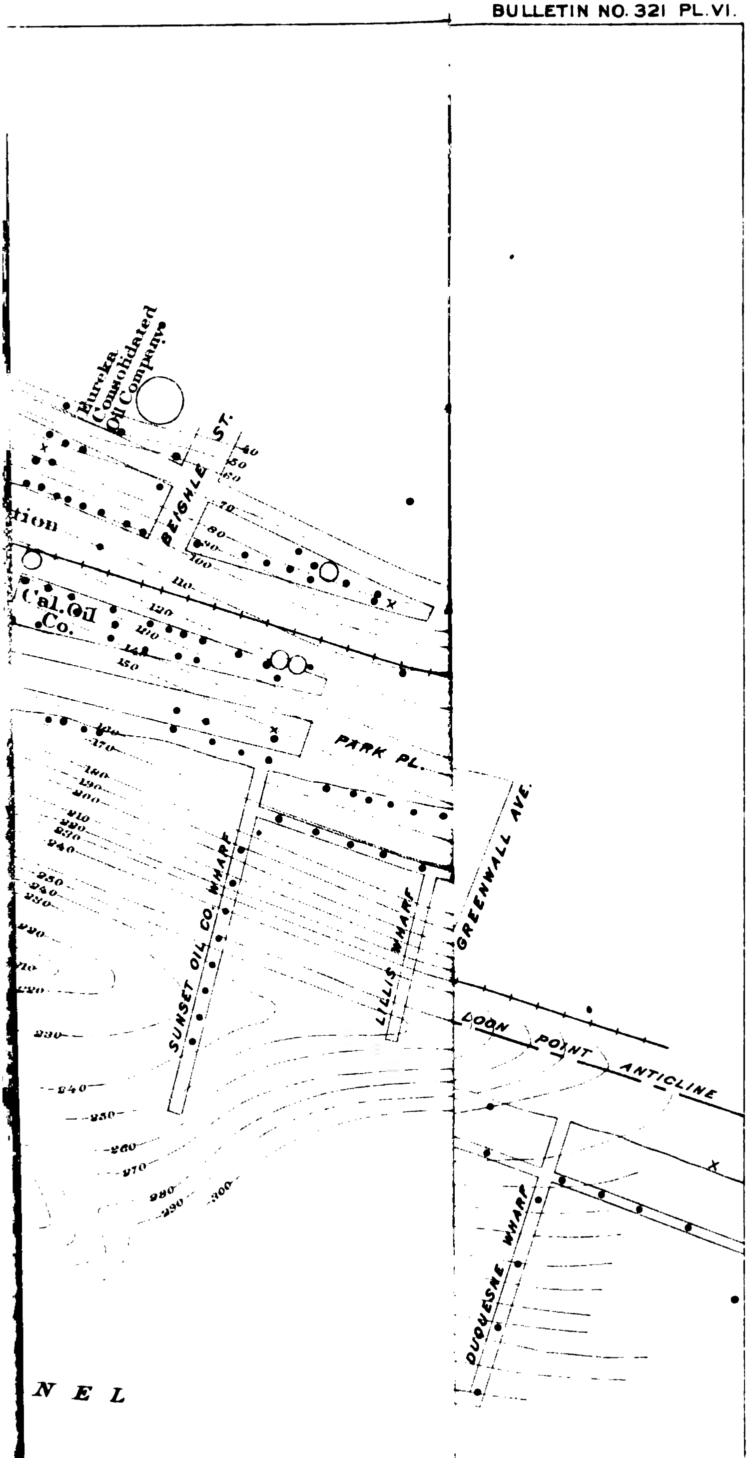
The range of hills northeast of Summerland was elevated by an anticline which later became faulted at its apex. This anticline will be referred to as the Arroyo Parida faulted anticline, as it passes along the canyon of Arroyo Parida for some little distance (see Pl. V, section *C*-*C*″). The fault exposes on its south side upper Topatopa sediments dipping steeply southward at angles as high as 70°, overlain by later formations with dips fully as steep, if not locally steeper. The lowest beds exposed on the north side of the fault are the prominent thick-bedded light sandstones at the base of the Sespe, which



GEOLOGIC SECTIONS ON LINES A-A' AND C-C' OF PLATE I.

A-A', From coast three-fourths mile east of Santa Barbara wharf northward to ridge east of Rattlesnake Canyon.
C-C', From coast 1 mile southeast of Serena N. 13° E. to summit of Santa Ynez Range. 1, Alluvium and Pleistocene gravel, sand, and clay; 2, Monterey (middle Miocene) diatomaceous shale and volcanic ash; 3, Vaqueros (lower Miocene) shale, sandstone, and limestone concretions; 4, Sespe (Eocene-Oligocene?) reddish conglomerate, sandstone, and shale; 5, Topatopa (Eocene) formation; 5a, Upper fossiliferous sandstone; 5b, Upper shale, oil bearing; 5c, Lower sandstone; 5d, Lower shale.


Cal. Oil
Co.



IRS THE DISTANCE BELO

dip at angles of 10° to 25° toward the overturned syncline lying between the fault and the Santa Ynez anticline. It is interesting to note in passing that this syncline is traceable for many miles east of the area under discussion and is probably the westward continuation of the syncline which passes through Ojai Valley and to which, in the opinion of the writer, that valley depression owes its origin.

Although the Arroyo Parida fault passes beneath the detrital material west of Toro Canyon, it is known to exist at least as far west as Ficay Creek. This is shown by the relations existing between the upper Sespe shales in the hills northwest of the bend in Ficay Creek and the lower Sespe sandstones in the ridge only a short distance to the southeast. It is impossible to determine what becomes of the fault still farther west, although where last known it is trending directly toward the complexly folded region north of Santa Barbara, and is believed to bear some relation to the puzzling disturbances in the rocks in the vicinity of Rattlesnake Canyon.

MINOR FOLDS NEAR THE COAST.

FOLDS EAST OF CARPINTERIA.

An area of complex fracturing and folding stretches along the coast from Carpinteria Creek eastward at least as far as the edge of the region shown on the map. The Monterey shale at the asphalt mine just south of the mouth of the creek is standing vertical; a short distance east of this the same rocks are intricately contorted and fractured, in some places having the appearance of a breccia (see Pl. III, *A*); while still farther east, near the edge of the mapped area, an anticline, with northeast dip of 30° and southwest dip of 45°, passes out into the ocean. East of the anticlinal axis the shale for some distance dips toward the north or northeast. The trend of the anticline is approximately parallel with the coast, and on a line with it, about half a mile east of the asphalt mine, an oil well has been sunk.

FLEXURES NEAR SUMMERLAND.

Two local flexures affecting the oil-bearing Fernando formation have been recognized near Summerland. One of these is a well-developed anticline striking west-northwestward from Loon Point, the axis being nearly coincident with the edge of the bluff for more than half a mile northwest of the point. The strike and dip of the exposed beds near the axis indicate that the anticline plunges southeastward and is undulating in the direction of the strike. Points of greater elevation in its trace are 150 yards southeast of the Duquesne wharves and also a short distance west of Loon Point. At these nodes the gypsiferous lower Fernando shale is brought up to view. The dips on the side of the anticline reach as high as 30° or 35°. The

flexure gradually dies out from the region of the easternmost group of wharves northwestward toward the main part of the town of Summerland, where it appears to lose its individuality on the southward-dipping flank of the Arroyo Parida anticline.

Another flexure (designated the Summerland fault and anticline on the structure map, Pl. VI), which appears to be a sharp and possibly locally overturned and faulted anticline, with a strike north of west, occurs in the Fernando beds near the edge of the bluff opposite the Becker and North Star wharves. (See section *B-B'* Pl. VII, and the Becker and North Star well sections A. and B, Pl. VIII.) The well logs indicate that this fold covers a rather small area, although its southeastern extension may be considerable. The dips along it range from 45° SW. to vertical in the Becker-North Star area, the petroliferous sandstones, conglomerates, and associated clays being affected. A disturbance of the Pleistocene beds along what is probably the trace of this anticline tilts them northeastward at angles ranging as high as 8° or 10° in the north end of the field. (See fig. 2, p. 34.)

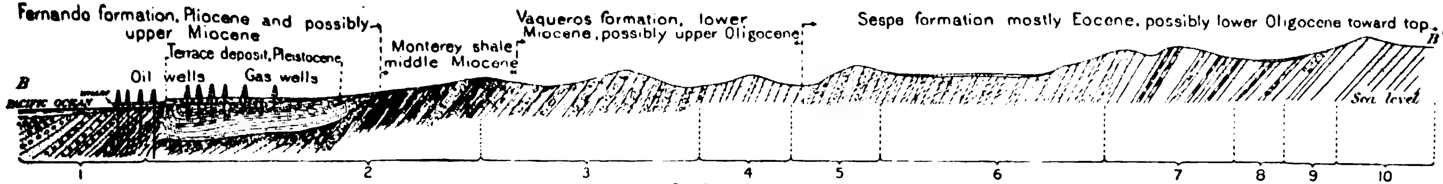
In addition to the two flexures just described, the well logs show one or two local wrinkles affecting the oil sands and associated layers in the region of the wharves; these are shown in the detailed sections and also on Pl. VI.

MONTECITO ANTICLINE.

An anticline striking about N. 70° or 80° W. passes into the ocean from the bluff opposite the cemetery a mile north of Montecito Landing. This fold affects the Fernando clay, sandstone, and conglomerate. The dip in the beds on either side of the axis ranges from 20° to 40°, the steepest being toward the southwest. The conditions of structure along the anticline appear favorable for the accumulation of petroleum, and although no surface indications are visible, it is probable that oil-bearing beds underlie the fold, possibly at a considerable depth, however.

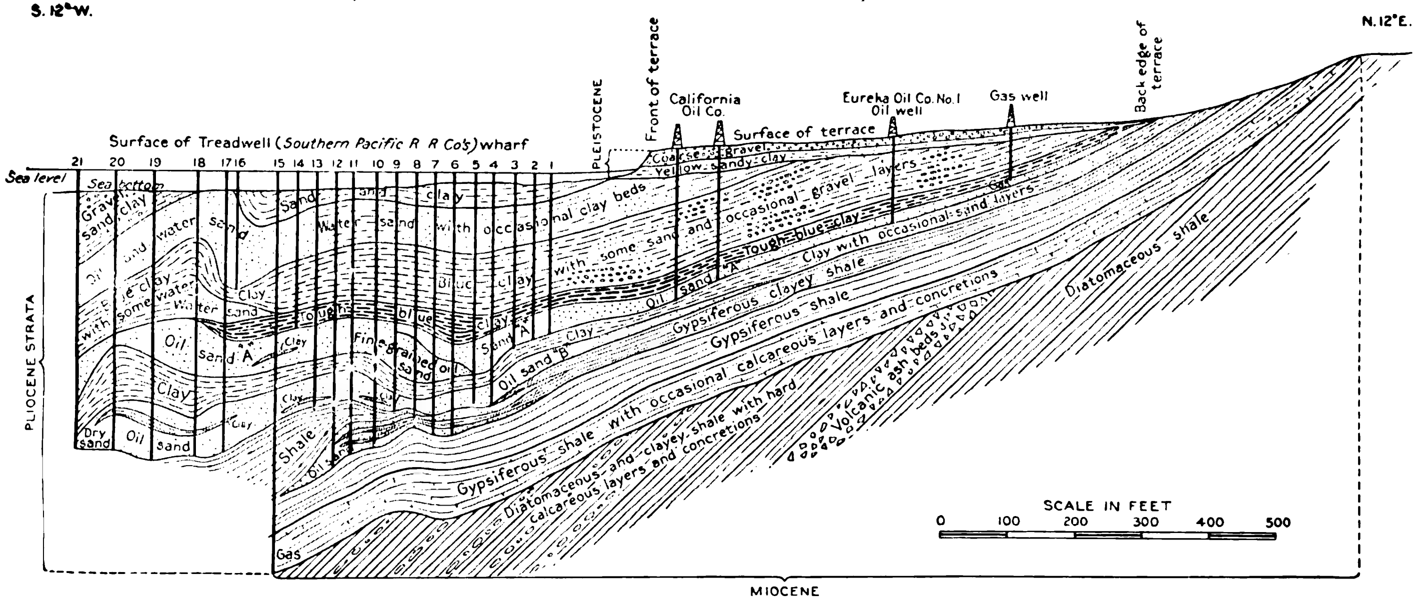
STRUCTURE NEAR SANTA BARBARA.

Detrital deposits obscure the structure in the Santa Barbara Valley, but from the southerly dips in the Fernando beds southwest of the city it is surmised that a fold similar to the Montecito anticline or else a fault affects the beds of Packards Hill. The structure of the coast west of Punta del Castillo was not studied.



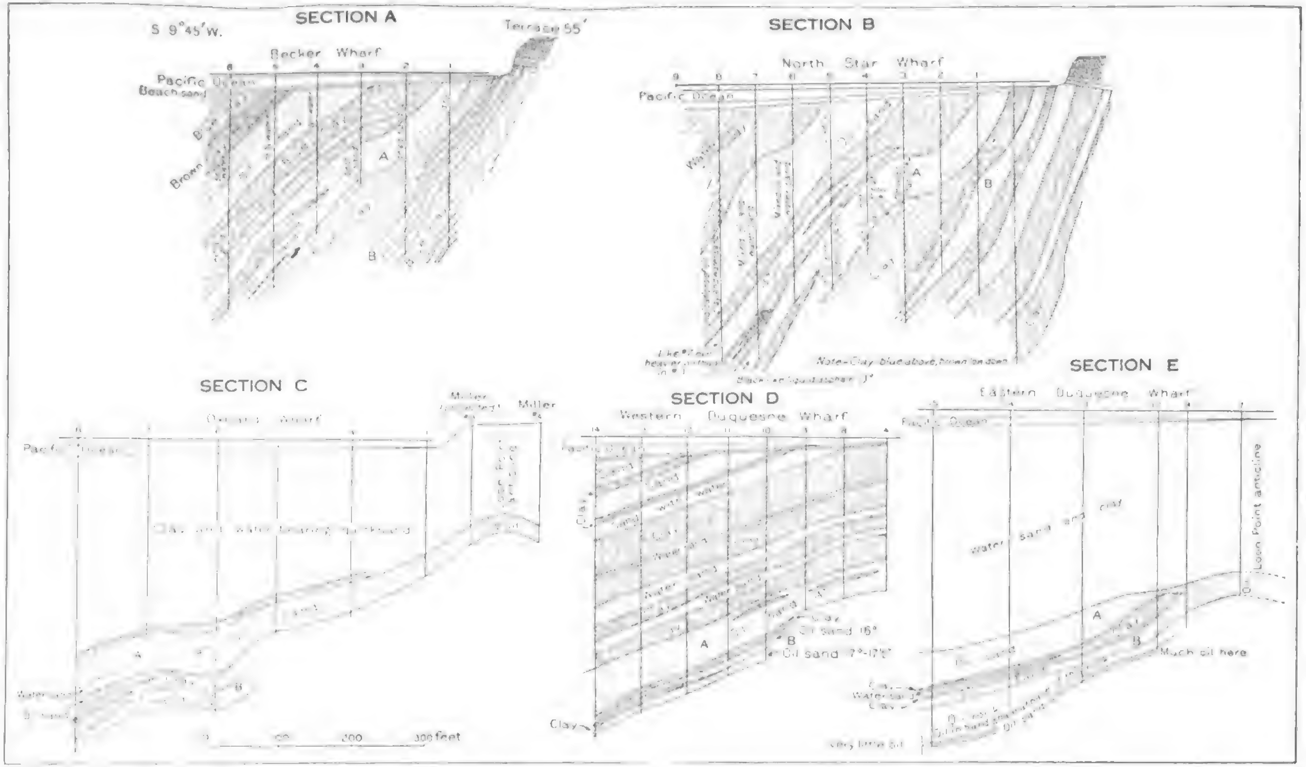
A. GEOLOGIC SECTION ON LINE B–B' OF PLATE I.

From a point northwest of Summerland N. 61° E. to knoll in forks of Toro Canyon, 2 miles northeast of Summerland.



B. SECTION THROUGH TREADWELL (SOUTHERN PACIFIC COMPANY'S) WELLS.

N. 12° E. to a point immediately northwest of big oil tank in Summerland. Section is about 1,000 feet west of Oxnard wharf. (See Pl. VIII. Section C.)



SECTIONS SHOWING RELATIONS OF OIL SANDS IN VARIOUS SUMMERLAND WELLS.

A, G. F. Becker Oil Company's wells Nos. 1 to 6; westernmost wharf in the field, about 300 feet west of North Star wharf. B, North Star wharf wells Nos. 1 to 8; about 1,100 feet west of Treadwell (Southern Pacific Company's) wharf (see Pl VII, *B*). C, Miller wells Nos. 4 and 8 and Oxnard wharf wells Nos. 1 and 4 to 8; about 800 feet west of western Duquesne wharf. D, Western Duquesne wharf wells Nos. 4 and 8 to 14; 400 feet west of eastern Duquesne wharf. E, Eastern Duquesne wharf wells Nos. 7, 9, and 12 to 15.

DESCRIPTION OF THE WELLS.

GENERAL STATEMENT.

The oil wells in the Summerland field are put down on the terrace upon which the town is situated, on the beach in front of this terrace, and on wharves which extend out into the ocean, some of them nearly a quarter of a mile. (See Pl. II, *A*, p. 20.) The wells range in depth from 100 to more than 600 feet, the shallowest being the northernmost on the terrace, the deepest those farthest south on the wharves. The oil is obtained from sands alternating with clay beds in the Fernando formation (upper Miocene or lower Pliocene), which dips almost due south at angles ranging from nearly 90° at the north end of the field to nearly horizontal at the south end. Only one productive sand, from 10 to 45 feet thick, is penetrated by the terrace wells, but in the wharf wells two, and in some three, oil sands occur.

For convenience of discussion, the field has been divided into the following sections, which are here treated in detail: Area west of Lookout Park; area north of the railroad; area between the railroad and the beach, and wells on the beach and wharves. (See Pl. VI.) In addition to these areas the gas wells in the town of Summerland and the oil wells near Loon Point, near Carpinteria, and in the mountains northeast of Summerland are briefly described.

AREA WEST OF LOOKOUT PARK.

Geology and structure.—The wells in the area west of Lookout Park penetrate the steeply dipping or disturbed beds flanking the Summerland anticline and fault, which extends from a point a short distance east of the edge of the bluff in the vicinity of the North Star wharf in a northeasterly direction toward the top of Ortega Hill. (See Pl. VI.) Dips of 80° or 90° occur in the sandstone and conglomerate beds at the shore end of the North Star wharf, but farther east the dip lowers to 45° or less. The well logs indicate a more or less irregular arrangement of the Fernando beds in the region of the Potomac wells, probably the result of their proximity to the line of disturbance to which reference has just been made. The strata penetrated consist of gravel near the surface and alternating sands and shale or clay lower down. Several oil sands are penetrated by some of the wells, but only one or two are productive. The productive beds are from 10 to 52 feet thick in the wells and are separated by clay, which varies materially in thickness from well to well. The sand is granitic and coarse textured, some of it approaching gravel, and in most places is "quick" or incoherent, flowing with the oil and necessitating considerable cleaning of the wells. The usual color of the formation in all the wells is brown or gray, but certain wells in

the triangular block west of Evans street and south of Wallace avenue have yielded a peculiar red material, which has been encountered in no other wells in the field, with the possible exception of some put down in the Monterey shale area in the northern part of the town.

The following two logs illustrate the character of the strata penetrated by the wells in this area:

Log of Williams's well, on top of Ortega Hill, Summerland.

	Thickness.	Depth.		Thickness.	Depth.
	Feet.	*Feet.*		*Feet.*	*Feet.*
Gravel	70	70	Blue shale	37	385
Sand and shale, water at 200 feet	130	200	Sand, with oil lighter than that in first sand	10+	395+
Shale	115	315			
Quartz sand, saturated with oil	24	339			
Blue clay, with wood fragments and sea shells	9	348			

Log of Potomac well, on south flank of Ortega Hill, Summerland.

	Thickness.	Depth.		Thickness.	Depth.
	Feet.	*Feet.*		*Feet.*	*Feet.*
Clay, sand, and coarse gravel	70	70	Clay	5	211
Dead oil sand	52	122	Gas sand	4	215
Clay	38	160	Oil sand	20	235
Dead oil sand	10	170	Clay	30	265
Clay	25	195	Water sand	11	276+
Oil sand with little oil	11	206			

Water occurs at several horizons in this area, being encountered at 200 feet in the Williams well (Ortega Hill) and at 265 feet in the bottom of one of the Potomac wells.

Wells.—All the wells in this area are drilled, the casing used being 4½ inches or a little larger. Productive sands are encountered at depths ranging from about 170 to 385 feet, the latter figure being in the Williams well on Ortega Hill.

Product.—The production ranges from something less than 1 barrel to 2 or 3 barrels a day, but the initial production for some of the wells is said to have been greater. The average for the Potomac group was in 1902 about 1¼ barrels a day each, and it has fallen off but little in the last four years.

The gravity of the oil averages about 15°, varying but slightly above or below this figure. The oil is fairly free from water when the wells are first drilled, but with the lapse of time the proportion of water increases. In 1902 the Potomac wells were yielding 1 to 4 per cent of water and 1 to 2 per cent of sludge with the oil.

Gas accompanies the oil in practically all the wells.

Companies.—Among the companies and individuals who have operated in this area are H. L. Williams, Potomac Oil Company, Roberson Oil Company, Churchill Oil Company, Larson Oil Company, Seaside Oil Company, and Miller Oil Company.

AREA NORTH OF THE RAILROAD.

Geology and structure.—The oil and gas wells north of the railroad, after passing through the Pleistocene, penetrate the beds near the base of the Fernando which dip at a rather low angle to the south. Beneath the Monterey-Fernando unconformity the Monterey beds probably dip steeply southward, as they do in the hills northwest of Summerland. Some of the drillers, however, have reported steep northerly dips (probably due to local overturning of the beds) in some of the wells in the shale. The Fernando beds dip very gently southward but thin rapidly toward the north, the oil sand decreasing from 25 to 12 feet within 200 or 300 feet.

The well logs indicate from 10 to 25 feet of soil, sand, and gravel (probably Pleistocene); 60 to 120 feet of fine sands and blue clays, with a persistent layer of blue clay at the bottom, and 12 to 25 feet of oil sand, the top of which is penetrated at depths of 70 to 145 feet.

Wells.—With the exception of the Cole dug well, all the wells in this section of the field of which there is any record are drilled, the casing usually being 4½ inches in diameter.

Product.—When the sand was first tapped the production of the wells ranged from 1 to as high as 12 barrels a day for some of the wells in the central part of this area, but the average at any time was never over 3 or 4 barrels. The Cole dug well, at the extreme east end of the productive territory, 4 feet in diameter and 90 feet deep, yielded but 3 barrels a day. The group of 12 Doulton & Wilson wells in the central part of the area are said to have averaged 10 barrels a day each in 1895, but fell off to 6 barrels each by July, 1896.

Companies.—The following are among the companies or individuals who have operated wells in the area north of the railroad: Alameda and Santa Barbara Development Company, Eureka Consolidated Oil Company, Stevens & Roberts, Doulton & Wilson, Bachus & Cravens, Loomis Oil Company, Dewlaney Oil Company, Cole Oil Company, Wakham Oil Company, Goodnow Oil Company, Williams & Easton, Turner & Darling.

AREA BETWEEN THE RAILROAD AND THE BEACH.

Geology and structure.—The conditions in the area between the railroad and the beach are a southward continuation of those found north of the railroad. The terrace on which the wells are sunk averages between 25 and 30 feet above sea level, and is underlain by Pleistocene beds which dip gently northward at the west end of the field but lie flat farther east. Beneath the Pleistocene the Fernando beds show dips ranging from 70° or 80° S. in the region about Lookout Park to 22° S. in the territory of the Seaside Oil Company, 400 or 500 feet farther south, and finally to practically horizontal in the eastern part

of the field. The wells first penetrate 10 to 20 feet of fine sand and 5 to 10 feet of sand and cobblestones, probably Pleistocene in age. These beds are followed by 150 to 170 feet of sand, with clay and some gravel, a persistent clay bed occurring at the bottom. The oil sand is encountered below the clay bed. It is 30 to 45 feet thick and underlain by clay. The oil sand becomes unproductive in the region a short distance northeast of the shore end of the Oxnard wharf, the eastern of two adjacent wells located here being entirely unproductive while the western once yielded a little oil. The following log of one of the Seaside Oil Company's wells located about 400 or 500 feet east of Lookout Park is typical for this area:

Log of Seaside Oil Company's well 400 or 500 feet east of Lookout Park, Summerland.

	Thickness.	Depth.		Thickness.	Depth.
	Feet.	*Feet.*		*Feet.*	*Feet.*
Adobe	10	10	Blue clay	20	155
Clay and "chalk"	5	15	Oil sand	30	185
Sand and bowlders	50	55	Quicksand (fine sand with oil and water)	20	205
Blue clay	60	115	Clay	1+	206+
Water sand	20	135			

Water is encountered in the sand above the clay layer overlying the oil sand, and also in the fine sand underlying the oil sand. At this lower horizon it is associated with some oil, the emulsion of the two making the sand "quick."

Wells.—The wells in this area are all drilled. They range from about 150 to 240 feet in depth, and penetrate the oil sand at 125 to more than 200 feet.

Product.—In their prime the wells produced as high as 15 barrels a day each, but the average was probably never more than 3 to 5 barrels. One group of wells which produced from 6 to 10 barrels a day each when first pumped, soon dropped to a daily average of about 3 barrels, which was held for two years. One of the Wilson wells (No. 2), which had an initial flow of only 3 or 4 barrels a day, suddenly rose to a production of 15 barrels a day soon after it started, and kept this up for over a year and a half, although the adjacent wells never averaged over 2 or 3 barrels a day each. It seems likely that this particularly good producer must have penetrated a rich crevice or locally extremely porous place in the oil-bearing bed. A group of wells opposite the Lillis wharf and south of the railroad increased in production when the wells opposite them across the track were abandoned.

The gravity of the oil ranges from 12° to 15½° Baumé, the lightest oil coming from the wells at the east end of the field. The average gravity for the entire area is probably about 13°. It is thought that the water which is pumped in varying amounts with the oil has had a

deleterious effect on its gravity, those wells producing the lightest oil pumping the least water. Traces of sludge accompany the oil and water in some of the wells.

Companies.—Among the companies and individuals who are now operating or have operated in this area are the following: Alameda and Santa Barbara Development Company, Doulton & Wilson, Forester & Treadwell, W. M. S. Moore, Seaside Oil Company, J. C. Wilson, California Oil Company, Miller & Williams, Roberson Oil Company, and Packard Oil Company.

BEACH AND WHARF WELLS.

Geology and structure.—The formations penetrated by the beach and wharf wells are similar to those found in areas to the north, except that the Pleistocene is lacking and in its place is a veneer of beach sand from 2 to 5 feet in thickness covering the Fernando sandstones, shales, and clays. Treadwell (Southern Pacific Company) well No. 15 encountered gas in hard shale at a depth of about 600 feet, and this is supposed to represent the bottom of the Fernando and the top of the Monterey in this part of the field. The Fernando dips southward over practically the whole region, although near the Treadwell wharf it has a local low northerly dip; at the shore end of the Oxnard and Duquesne wharves the beds assume a low dip preparatory to passing over the Loon Point anticline. From the east end of the field westward the southerly dip in the Fernando is as follows: Eastern Duquesne wharf, 15°; western Duquesne wharf, 20°; Sea Cliff wharves, 21°; Oxnard wharf, 22°; Treadwell (Southern Pacific Company) wharf, 15° to low north dip; North Star wharf, 10° to 50°; and Becker wharf, 50°. As shown by the sections (Pls. VII, VIII), there are two or three local crumples in the beds, the one first showing in the Oxnard section and passing thence northwestward through the Treadwell section and so on into the region north of the North Star and Becker wharves being the most persistent. (See Pl. VIII, p. 38.) Some faulting probably accompanied the folding that produced this wrinkle, especially toward its north end. The Loon Point anticline dies out to the north of the east end of the beach area, so that it apparently exerts little influence on the accumulation of the oil over most of the territory west of the Sunset wells. A small but nevertheless noticeable crumple in the oil sand occurs between Becker wells Nos. 2 and 3 and between North Star wells Nos. 2 and 3.

Several oil sands are met in the wells, the principal one (A in fig. 3 and Pls. VII, *B*, and VIII) being a continuation of the single sand found in the areas to the north. All of these sands, with the exception of the "oil rock" found in the wells at the east end of the area, are typical quartzose sands ranging from grains the size of a mustard seed up to

pebbles of considerable size. They are largely "quick" or "heaving" sands, requiring frequent removal from the wells. In fact, many of the wells pump considerable sand with the oil, the separation of the two being accomplished in a "sand box." Sand A ranges in thickness from about 25 to nearly 75 feet, being thinnest near the shore and thickest toward the south end of the wharves. The evidence offered by the wells indicates that the Fernando was laid down under rapidly

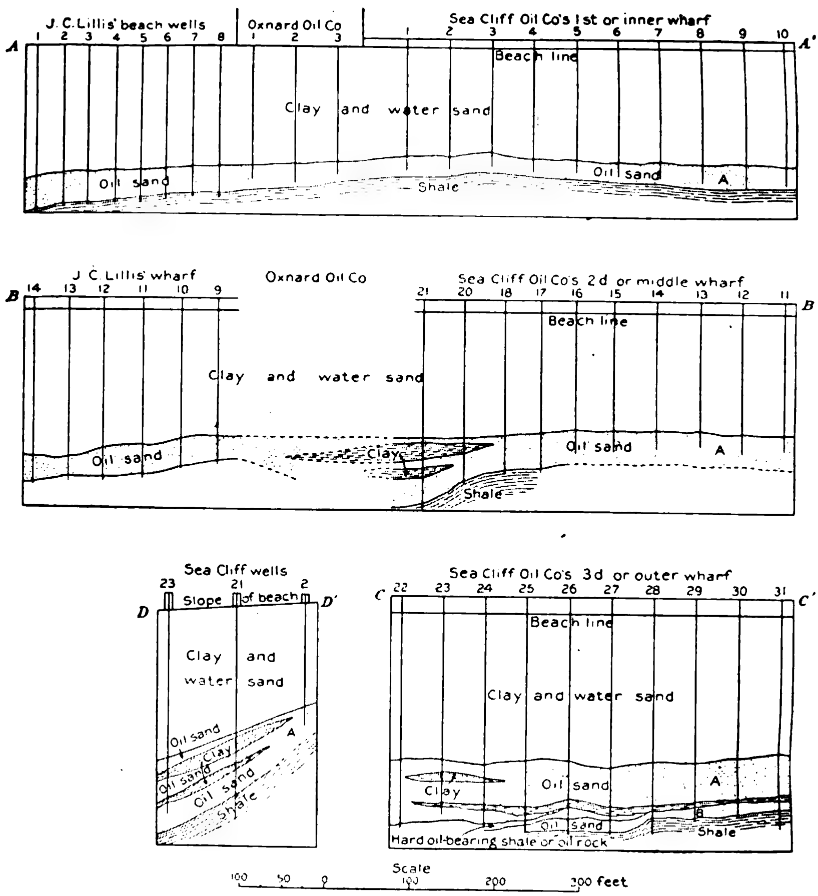


FIG. 3.—Geologic sections through the Lillis, Oxnard, and Sea Cliff wells. *A-A'*, *B-B'*, and *C-C'* show the relations of the oil sands along the strike; *D-D'*, the relations across the strike. A designates principal oil sand. See Pl. VI (p. 36) for location of sections. Figures denote number of wells.

changing conditions, which have resulted in great variations in the thickness and composition of the same bed within short distances, these variations being very marked in the oil sands, as well as in the associated layers. (See sections in fig. 3 and Pls. VII and VIII.) The sands contain in many wells included clay lenses and are locally split up by intercalated clays. The variation in the sands is apparent not only in the sections which cut across the strike, but also in those which

parallel the strike, as is shown in fig. 3. Sand A is overlain throughout this area, as well as throughout other parts of the field, by a persistent tough clay layer which appears to be almost completely impervious to the oil below and the water above it. At the north end of the area (see North Star and Becker sections, Pl. VIII) a productive oil sand is intercalated in the lower part of this layer. To this stratum and to similar less important clays above the other sands the retention of the oil in the porous layers is due, inasmuch as these clays act as barriers to the upward migration of the oil toward the surface from the Monterey shale below the unconformity. Had it not been for the clays nearly all of the oil would have escaped to the surface to form asphalt deposits, such as those at Carpinteria and other places along the coast, where the Monterey shales are petroliferous, but where the conditions are not as favorable for the accumulation of oil as they are at Summerland. Sand A is underlain by a clay stratum which in turn overlies sand B, a productive layer varying from a mere stringer to a bed 25 or 30 feet thick. Still another sand below, separated from B by clay, is struck in some of the wells. The oil sands below A are not found north of the shore-line wells, indicating that they pinch out and should be considered more in the nature of local lenses of sand rather than beds continuous over considerable areas. The "oil rock" previously mentioned occurs below the B sand in the Duquesne and adjacent wells, and consists of hard shale in which is found an oil 1° or 2° lighter than that occurring in the true sands. Oil is also derived from crevices in the clay in one of the dug wells at the west end of the field, these crevices conforming in general slope to the dip of the beds.

The following are two typical logs from this area:

Typical log of well on the shore line, Summerland.[a]

	Thickness.	Depth.		Thickness.	Depth.
	Feet.	*Feet.*		*Feet.*	*Feet.*
Yellow clay	100	100	Blue clay	50	230
Sand, with water	20	120	Oil sand A (oil 12° to 14°)	50	280
Blue clay	30	150	Blue shale	20	300
Sand, with water	30	180	Oil sand	100	400

[a] Watts, W. L., Bull. California State Mining Bureau, No. 19, 1900, p. 102.

Log of one of the Duquesne wells, typical of those at east end of wharf area, Summerland.

	Thickness.	Depth.		Thickness.	Depth.
	Feet.	*Feet.*		*Feet.*	*Feet.*
Alternating clay and water sand	330	330	Second oil sand	14	405
First oil sand (A)	45	375	"Oil rock" (shale with traces of 16° to 17° oil)	48	453
Clay	6	381	Oil sand (slight amount of oil)	5	458+
Water sand	4	385			
Clay	6	391			

Above the persistent clay layer over sand A is a series of alternating sand and clay beds carrying water. In the region extending from the Becker wharf to the Treadwell (see Pl. VII, *B*, and Pl. VIII, section B, p. 38), a 75-foot stratum of sand carrying some oil with the water overlies the clay. The relations of the oil and water in this bed as indicated by the well logs are very interesting, as showing that under certain conditions water and what is apparently an emulsion of water and oil may occupy the same bed, with the water above or up the slope from the oil.

Water is encountered at the base of the oil sand in Oxnard well No. 8, at the south end of the wharf, but does not extend northward or up the slope to No. 7. This occurrence indicates that the water under hydrostatic pressure is following up the oil and will in time probably replace the oil as the latter is pumped from the sands. Water has always been troublesome in the beach and wharf area, but much of the difficulty with it has arisen from faulty manipulation of the wells. There is evidence, however, that in many of the wells the water is following up and replacing the oil. In speaking of the oil and water in one stratum of sand, Mr. Becker informed Mr. Eldridge that he found the oil in the upper half of the bed and the water in the lower half. Just after piercing the stratum and while the gas pressure is maintained, the oil remains distinct from the water, but after the gas pressure is relieved the oil is gradually permeated by the water, with a deterioration of the oil itself, viz, a lowering of the gravity of the oil after a separation of the two components of the emulsion. It is said that no water entered with the oil from sand B for over a year after the wells penetrated it. Sulphur water is encountered in a clay lens in one of the Marine Oil Company's wells and also in the clay between the first and second oil sands in the same wells.

Wells.—With the exception of three dug wells on the beach at the north end of the area, all of the wells are drilled, the casing used ranging in diameter from about 4½ to 12 inches. "In drilling beneath the water a casing larger than that needed for the drill hole is put down to the floor of the ocean and forced into the bed rock until the ocean water is securely shut out of the drill hole. This is called a conductor, and the casing of the well is put down inside of the conductor."[a] The main oil sand (A) is penetrated in the wells at depths of 125 to about 325 feet. The range of depths for the different wharves is as follows: Eastern Duquesne, 160 to 315 feet; western Duquesne, 200 to 325 feet; Sea Cliff, 125 to 200 feet; Oxnard, 125 to 290 feet; Treadwell (Southern Pacific Company), 200 to 250 feet; North Star, 5 to 350 feet; Becker, 5 to 310 feet.

[a] Watts, W. L., Bull. California State Mining Bureau No. 19, 1900, p. 102.

Product.—The individual production of the drilled wells varies from a fraction of a barrel to that of one of the Duquesne wells, which is said to have had an initial production of 100 barrels a day. It is claimed that this well continued this production, which is phenomenal for this field, for six months, but finally fell off to an average of 3 or 4 barrels a day. The general average for the wharf wells at the present time is between 1 and 2 barrels a day each; this is probably less than one-half the average for the field when it was in its prime.

Of the dug wells, the best producer was a 60-foot hole in the bottom of which was sunk 17 feet of $9\frac{5}{8}$-inch casing. This is said to have been capable of producing 100 barrels a day at one time. The other dug wells yielded from 3 to 10 barrels a day each.

The best production has usually been in the most-disturbed strata. The Williams wells, for instance, in the steeply dipping beds at the north end of the field, have been, with only a few exceptions, the best producers. Oxnard No. 6, the best producer of the group, is located on a local flexure (see Pl. VIII, section C, p. 38), and so there are other cases. No. 12 of the eastern Duquesne wharf, which is said to have been a 100-barrel well, probably tapped a locally rich place in one of the lower sands. The initial production of each well is ordinarily about twice its production after one year and three or four times its production after two years. The subjoined record of one of the Duquesne wells illustrates the rate of decline in production:

Decrease of production in one of the Duquesne wells, Summerland.

	Barrels a day.		Barrels a day.
May, 1898 (initial flow)	6	February 16, 1900	$2\frac{1}{2}$
June 8, 1899	3	February 22, 1900	$2\frac{1}{4}$
January 1, 1900	$3\frac{7}{10}$	August 25, 1900	$1\frac{3}{4}$

The wells down the dip usually give a slightly better yield than those higher up in the same stratum, although in the case of the wharf wells this may be due in part to a thickening of the strata. The good yield of some of the wells farthest south on the wharves is also explained by the fact that they tap the second and third oil sands, which have proved to be in places exceptionally productive. In the eastern Duquesne wells, which penetrate two sands, no well pumps from both strata, but each stratum is pumped in alternating wells, the lower stratum being the more productive. In the western Duquesne wells an average of $4\frac{1}{4}$ barrels a day was yielded by each of the 14 wells along the beach which tapped the upper sand, while the six wharf wells, which obtained their petroleum from the lower stratum, produced an average of $6\frac{2}{3}$ barrels per day.

The oil obtained from the wharf and beach wells ranges in color from black to olive-brown, the latter being the lighter, and in gravity from 12° to 18°, with an average of about 15° Baumé. The heaviest oil comes from the main oil sand (A) in the beach wells throughout

the central part of the area; the 14° to 15° oil from the same sand in the great majority of the wharf wells; the 16° oil largely from the second or B sand; the 17° to 17½° oil from the "oil rock" below the main oil sand in the eastern part of the field; and the oil, which is said to have tested 18° from Williams No. 2 well, in the highly tilted beds at the extreme west end of the field. Certain wells on the beach and edge of the bluff, between the Becker and Treadwell wharves, are said to have been abandoned because the sand yielded liquid asphaltum too heavy to pump. Similar asphaltum is also reported in sand A at the bottom of North Star No. 8, although the oil in the same stratum less than 100 feet farther north, up the dip, was reported as of 15° gravity.

It is said that in the Sea Cliff wells the oil in the upper or A sand is lighter along the beach than southward and seaward down the dip. Exactly the opposite condition is reported in the steeply dipping beds in the North Star section, where (with the exception of the very heavy oil in the bottom of No. 8) the lightest oil is that from the well farthest out on the wharf. This occurrence of the lightest oil in the beds farthest down the dip is by far the most common in the California fields so far examined by the writer. The conditions at the Sea Cliff wells may be explained on the assumption that the oil reached sand A through crevices along the axis of the Loon Point anticline (see Pl. VI, p. 36) and spread southward down the dip of the beds, losing in gravity as it migrated.

Water, sludge, and gas accompany the oil in most of the wells of the area. The product ranges from an initial yield of oil containing practically no water to an emulsion containing 98 or 99 per cent of water. The average emulsion coming from those wells which have received fair attention contained from 18 to 22 per cent of water at the time of the writer's visit (1906). Many neglected wells produced practically all water, with only occasional traces or blebs of oil. It is said that well No. 14 on the eastern Duquesne wharf pumped practically pure oil for the first six months, after which water gradually increased up to 22 per cent, but that the net production of oil at the time it contained 22 per cent of water was greater than when it pumped oil alone. The greater fluidity of the emulsion in this case seemed to more than compensate in increased production for the loss of quality of the oil.

Sludge is pumped with the oil, its amount ranging from a trace up to 45 per cent.

Companies.—The companies which have at one time or another operated the beach and wharf wells, named in the order of the wells from east to west, are the Duquesne (Keith and Williams wharves),

Southern Pacific, Sea Cliff, Oxnard, Lillis, Sunset, W. M. S. Moore, Treadwell (Southern Pacific Company), Marine, Knapp, McCall, Santa Barbara Oil and Mining, North Star, Becker, and Williams.

GAS WELLS IN THE SUMMERLAND FIELD.

General statement.—In addition to the gas which accompanies the oil in practically all the wells in the Summerland field there are more than a dozen wells which have produced nothing but gas. Though the flow of these wells was more or less powerful at first, they were quickly exhausted and all are now abandoned.

Geology and structure.—Some of the wells obtained their gas from the sands near the base of the Fernando formation, while at least three are believed to start down in the Monterey shale and penetrate gas accumulations in this formation. In both cases the beds dip to the south, the Fernando lying at a low angle unconformably over the Monterey, which is believed to be steeply tilted. The strata that yielded the gas in the Fernando are believed to be practically at the same horizon as sand A, which produces the oil in the wells a little farther south. In one of the Cone wells, in the eastern part of the town, the gas occurs at 600 feet below the surface, while oil is obtained 25 feet farther down. This occurrence, together with the general position of the gas wells at the top of the Summerland monocline, is interesting in substantiating the theory that wherever oil and gas occur separately in the same bed the gas will always be found at the top. In fact, the Summerland field as a whole furnishes a good illustration of the conditions postulated by the anticlinal theory, which states that where water, oil, and gas are found separately in the same bed the water will be found lowest, the oil next, and the gas at the top. The A. C. Doane well, at the southwest corner of Wallace avenue and Evans street, is typical of those which obtain gas from the Fernando oil-bearing horizon. It passes through reddish clay to 70 feet and gas sand to 83 feet, the clay forming the impervious cap.

In all the wells in the Monterey the gas was found under a hard limy shell layer, which had apparently been impervious to the gas. Traces of oil occur in the sandy layers in these wells below the level of the gas. The following log of one of the Darling Brothers' wells in the northwestern part of Summerland is typical of the gas wells in the Monterey shale.

Log of Darling Brothers' gas well on lot 32, block 25, Summerland.

	Thickness.		Depth.	
	Ft.	*in.*	*Ft.*	*in.*
Black adobe soil	5	0	5	0
Blue clay	80	0	85	0
Hard limestone	0	4	85	4
Sand (first gas)	1	0	86	4
Light shale	9	8	96	0
Limestone	0	2½	96	2½
Sand (second gas)	0	10	97	½
Light shale	32	11½	130	0
Hard limestone	1	0	131	0
Sand (third gas)	1	6	132	6
Chocolate-colored shale	18	6	151	0
Sandstone	10	0	161	0
Hard limestone	1	0	162	0
Sand (fourth gas)	1	4	163	4
Red shale	93	8	257	0
Sandstone	24	0	281	0
Black shale	66	0	347	0
Chocolate-colored shale	75	0	422	0
Hard limestone	1	6	423	6
Sandstone (specks of oil in bottom 5 feet)	100	6	524	0

Production of the wells.—The gas wells range in diameter from 2½ to 4½ inches, the shallowest usually being the smallest. The pressure of the gas was strong at first, but gradually fell off. One well, 104 feet deep, is said to have thrown mud and dirt 40 feet in the air when the gas sand was first penetrated. One of the Darling wells started in 1891 with a pressure of 8 pounds to the square inch and furnished gas to 17 families. In 1895 the pressure had fallen to 1 pound to the square inch. The three Cone wells supplied 20 families at first, but in four years fell off until they yielded barely enough gas for 3 families. The Cone wells had about the most enduring supply of all in the field.

One of the most interesting phenomena in relation to the gas supply in the gas wells and oil wells is the influence of the weather or denseness of the atmosphere on the flow. In speaking of the Darling Brothers' wells, Watts says:[a] "It is stated that during a north wind these wells yield a strong flow of gas, but when the wind ceases the gas ceases to flow and a current of air is drawn down the well for several hours. In one instance, the latter phenomenon was noticed to continue for two days before inflammable gas again flowed from the well." It would seem that such phenomena would result in a dangerous mixture of air and gas, but so far as the writer is aware no serious accidents accompanied the use of the gas for domestic purposes. In the Doane wells a heavy north wind caused the cessation of the gas flow entirely, this action being exactly contrary to the phenomena noted in the Darling wells. The gas in some of the oil wells on the beach was said to have increased in volume and the wells to have pumped better at high tide and in stormy weather. It

[a] Bull. California State Mining Bureau No. 11, 1896, p. 56.

was also noted that when the Santa Barbara Oil and Mining Company's well No. 6, on the edge of the bluff, was pumped the gas flow ceased in No. 11, which was located 30 feet farther north.

SUMMARY OF CONCLUSIONS CONCERNING THE OIL.

The oil in the Summerland field originates by a slow process of distillation from the diatoms and other organisms in the Monterey (middle Miocene) shale, which is abundantly developed in the region. After its formation quantities of the oil migrate upward, largely through joint cracks, under gas or hydrostatic pressure, and accumulate in the Fernando formation in porous sandstones under relatively impervious clay layers. The reason that the oil does not continue its upward migration through the Fernando to the surface is because the plastic condition of certain clay beds in that formation precludes the production of cracks that could act as channels for the oil. In certain places, however, notably at the north end of the field, the Fernando beds have been so steeply tilted that some of the oil has migrated along the sandy layers and accumulated, with a loss of volatile constituents, in the unconformably overlying Pleistocene sands and gravels.

The migration, accumulation, and characteristics of the oil are largely influenced by the composition and structure of the containing formation. The composition of the Monterey shale and certain portions of the shale at the base of the Fernando is such that the oil can migrate through them readily only when they are in a more or less fractured condition. As a result of this characteristic the largest accumulations of oil in the Monterey occur in the more gently folded beds, such as along the anticline east of Carpinteria, while the important deposits in the Fernando lie over or near the more intensely fractured portions of the Monterey.

The migration of the oil and its accumulation in the porous members of the Fernando are governed largely by the structure. The transference and collection appear to vary with the degree of dip, the greatest accumulations, other things being equal, occurring in the most highly tilted strata. This is illustrated by the greatest producers of this region, most of which penetrate the steeply dipping beds at the north end of the field.

The oil deteriorates with upward migration both in the Monterey shale and in the Fernando formation. This deterioration in the Monterey is exemplified by the Rincon well, which yields oil of 20° gravity, whereas heavier oil and even asphaltum is obtained at the neighboring Monterey outcrops. In the Fernando formation the wells on the western Duquesne wharf offer a striking illustration, the gravity of the oil here being 17° to 17½° in the lowest oil stratum, 16° in the next, and 14° in the uppermost. The Oxnard and several

other groups also present good examples, the lower sand in the Oxnard wells yielding 15¼° oil, while that in the upper sand is 14°. In its migration upward through sand A in the Becker wells the oil declines in gravity from 15° to 14° and finally to 13° within a horizontal distance of less than 150 feet up a 45° slope. (See Pl. VIII, section A, p. 38.) An apparent anomaly occurs in this same group of wells, heavy oil of 13° or less occurring down the dip below and in the same sand with the 15° oil. Another apparent anomaly is shown in the Oxnard section (Pl. VIII, section C), in the occurrence of 15½° oil in the Miller wells at a much higher point than the 14° oil in the wells out on the wharf. This occurrence may be explained on the hypothesis that the Miller oil migrated upward through the joint cracks in the heart of the Loon Point anticline rather than into sand A at points on its flank and thence up along the sand stratum. An alternative but less likely explanation of such phenomena is that for some reason the oil loses in gravity as it passes upward in the steeply dipping beds, while in beds of low dip the lightest oil is found at the top. Other things being equal, it is generally true that lighter oil comes from the finer sediments.

In any closed, tilted reservoir, such, for instance, as sand A, the water, oil, and gas separate according to their specific gravities, the water occurring down the slope, the oil above this, and the gas in the uppermost parts of the bed. Within the reservoirs, especially in those portions which are less steeply inclined, the oil and water may occupy adjacent zones parallel to the bedding planes, with no parting of clay or other impervious matter between. Neither the oil nor the water in such cases is pure, but each contains greater or less amounts of the other. It is because of the accumulation of the oil in the top of the oil sand in the manner described above that many of the wells penetrate only a portion of the stratum. (See fig. 3, sections *A–A′* and *B–B′*, p. 44.)

The association of oil with water has a deleterious effect on the gravity of the oil. For example, oil pumped from a certain sand in the Summerland field had a constant gravity until water began to enter the well, when it was noticed that the gravity of the oil after separation from the emulsion was less than it was before the water came in.

WELLS AT OTHER LOCALITIES IN THE SUMMERLAND DISTRICT.

WELLS NEAR LOON POINT.

Several prospect wells have been put down in the Fernando formation near Loon Point, about a mile east of the Summerland field, but none were successful, although oil sands with traces of oil were penetrated in most of them. It is the opinion of the writer that the

paucity of petroleum is due to the position of the Fernando beds, which are believed to overlie here the nonbituminous Vaqueros rather than the petroliferous Monterey as they do farther north in the Summerland field. The position of the Loon Point wells relative to the anticline is apparently advantageous and the only reason that can be assigned for their nonproductiveness is that stated above.

Some of the wells attained a depth of 500 feet, but none were ever operated. The Fischer dug well, one-fourth mile north of the point, was 124 feet deep and reported small quantities of heavy dark-green oil. The following log of the Nott & Webber well, put down from the end of a 310-foot wharf one-half mile west of Loon Point, is characteristic of the wells in this vicinity:

Log of Nott & Webber well, one-half mile west of Loon Point.

	Thickness.	Depth.
	Feet.	*Feet.*
Sandstone, blue clay, and occasional 2-foot to 3-foot sand and gravel beds with water.	380	380
Brown and chocolate-colored shale, with stratum of water tapped at 460 feet flowing over collar	150	530
Clay, with streaks of oil sand carrying oil	30	560

Water in this well would stop flowing when the well next to the southernmost on the Duquesne wharf, three-eighths of a mile west of Nott & Webber's wharf, was pumped. When the Duquesne well stopped pumping Nott & Webber's well would flow again, but water always reached the top of the casing in the Nott & Webber well, even when the Duquesne well was pumped. It was calculated that the Nott & Webber well was in strata 150 feet deeper than that of the Duquesne, which contained the water.

WELLS NEAR CARPINTERIA AND RINCON CREEK.

Several wells, at least one attaining a depth of over 3,000 feet, have been sunk on the lowlands in the region near Carpinteria and the mouth of Rincon Creek, 5 to 8 miles east of Summerland. Traces of oil were found in all of them, but none so far have been highly successful. In all the wells the strata penetrated beneath the superficial Pleistocene deposits have been the Monterey (middle Miocene) bituminous shale, which lies in steeply dipping positions throughout this coastal belt.

The most important and deepest well is that of the Columbia Oil and Asphalt Company, located on the north side of the railroad one-half mile east of the asphalt mine at Carpinteria. It is put down in line with the axis of a sharp anticline which extends into the ocean about a mile east of the mouth of Carpinteria Creek, near the edge of the area shown on the map. No definite information concerning the well was obtainable at the time of the writer's visit (October,

1906), but the following notes were gleaned from various sources: The well penetrates shale throughout the greater part of its depth, is about 3,000 feet deep, and encounters artesian water with a head of 12 feet at 100 to 150 feet, asphaltum at 1,200 to 1,400 feet, and oil in sandy layers in the lower 100 feet. The oil in the sump is black and heavy, although it is said by the operators that oil of 37° gravity was struck near the bottom. The oil is accompanied by a strong gas pressure. Gas was also encountered with the asphaltum between 1,200 and 1,400 feet, forcing the asphaltum up in the hole for a distance of 180 feet when first struck. Only a small amount of oil was on the sump, indicating that the production of the well is probably not large.

Several years ago a well was sunk in the shale at the edge of the bluff about one-fourth mile east of the asphalt mine. Heavy oil was struck, but it was too viscous for pumping, and the well was abandoned. The casing of this hole still protrudes from the ground, and a heavy oil accompanied by considerable gas is slowly escaping from it. It is said that a second well was sunk a short distance farther northeast, but that no oil of consequence was encountered in it. As the first well is near the northern limit of a highly disturbed zone, it seems very likely that the reason no oil was encountered in the second well was because it penetrated beds which were so little fractured that the oil had no channels of migration through them.

In 1894 a 4 by 6 foot well was dug to a depth of 354 feet by P. C. Higgins, on the seashore one-half mile west of the asphalt mine. Purplish bituminous shale, with casts of the fossil *Pecten peckhami* Gabb, was the only formation penetrated, and no oil was encountered.

A 400-foot well was drilled by J. Heath on the Hill ranch just north of the mouth of Rincon Creek, oil being struck in small quantities from 150 feet downward.

Watts [a] gives the following reference to prospect wells of the Arctic Oil Company east of Carpinteria:

> Well No. 1, 7 miles south of Rincon Creek, 1,825 feet deep; formation, red sandstone; no oil. Well No. 2, 50 feet distant from well No. 1, 2,100 feet deep; formation, red sandstone; no oil. Well No. 3, on Southern Pacific Railroad 1¼ miles east of Carpinteria; conglomerate and sandy shale to 700 feet; shale and sandstone to 1,200 feet; liquid asphaltum; well abandoned.

The conglomerate here mentioned is probably the Pleistocene gravel and sand, which overlies the Monterey shale to a depth of over a hundred feet in the region northeast of Carpinteria.

At the time of the writer's visit to Carpinteria (October, 1906) it was reported that a well was being sunk at Shepards, 2 miles northeast of the mouth of Rincon Creek, but no data concerning its depth or the formation penetrated were obtainable.

[a] Bull. California State Mining Bureau No. 19, 1900, p. 104.

WELLS IN THE MOUNTAINS NORTHEAST OF SUMMERLAND.

Several wells have at different times been put down in the Topatopa formation (Eocene) in the mountains east and northeast of Summerland. The wells have all been located near oil springs or seepages, and have without exception yielded traces and some of them commercial quantities of oil. Light yields and lack of proper transportation and market facilities have discouraged development, and at the present time none of the wells are being operated. Among the wells are those of the Santa Barbara Oil Company in Oil Canyon, the Occidental Mining and Petroleum Company in Toro Canyon, the Santa Monica Oil Company in Santa Monica Canyon, and the Pinal Oil Company at the mouth of Arroyo Parida. These will be briefly described.

Two wells were drilled by the Santa Barbara Oil Company in Oil Canyon about $3\frac{3}{4}$ miles northeast of Summerland. The rocks here exposed are the overturned upper Topatopa shale, which dips steeply at angles ranging from 60° N. to vertical; oil springs occur in them in the immediate neighborhood of the wells. The wells start down in the shale, but may penetrate to the stratigraphically higher but actually lower upper-sandstone belt. The wells are between 500 and 600 feet deep, and yielded small quantities of oil and much gas.

Seven wells and one tunnel have been sunk by the Occidental Mining and Petroleum Company in Toro Canyon about $3\frac{1}{4}$ miles northeast of Summerland and three-fourths of a mile west of those of the Santa Barbara Oil Company just described. The formation at the Occidental wells is the same as that in Oil Canyon, and the wells doubtless derive their oil from the same zone. The wells range in depth from 200 to 1,100 feet. Four of them were classed as productive and three dry, although the latter contained traces of oil. No. 1 is said to have produced a total of 5,000 barrels and No. 5 was rated as a 5-barrel well; the average for the productive wells was about 2 to 3 barrels a day each. In August, 1895, only one well was pumping, and the oil from this was largely mixed with water. The oil is black and of 17° Baumé gravity when it first comes from the wells, but on standing for a little while drops to 14°. The tunnel is 511 feet long and runs in a N. 10° E. direction into the mountains. It penetrates sandstone composed of quartz, feldspar, and green and reddish minerals, interbedded with the greenish shale. It yielded little oil but much water, and the latter is now being used in Summerland. An analysis of this water is given on page 24.

The well of the Santa Monica Oil Company is located 2 miles north of Carpinteria, near the mouth of Santa Monica Canyon. It starts down in the lowest Sespe sandstone, which here dips 60° S. 10° W., and penetrates the alternating sandstone and shale of the uppermost

Topatopa. A yield of 8 barrels a day of 18° amber-colored oil accompanied by strong gas pressure was encountered at 400 feet. At 700 feet a strong flow of sulphur water "drowned out" the oil and the well is now abandoned.

The Pinal Oil Company is putting down a well at the mouth of Arroyo Parida Canyon, about 3¼ miles east of Summerland. It penetrates the lowest Sespe sandstone and the uppermost Topatopa alternating sandstones and shales, which here dip 60° S. It is thought that the well will reach the oil in sands under a certain shell at a depth of something more than 1,000 feet.

WELLS WEST OF SUMMERLAND.

Several wells have been drilled in the region west of Summerland, but few data concerning them are available. The following references by Watts[a] are self-explanatory:

Illinois Oil and Asphalt Company.—Has a well on the seashore at Montecito. Formation, yellow clay and sand to 200 feet; blue clay and quicksand, with gas, to 260 feet; blue shale to 280 feet. Unfinished June, 1900.[b]

Santa Barbara and Naples Oil and Land Company.—The territory operated by this company is near the seashore about 15 miles west of Santa Barbara. In June, 1900, this company was drilling a well, the formation penetrated being principally shale to a depth of 450 feet, with some showing of gas and oil.

CONCLUSIONS CONCERNING FUTURE DEVELOPMENT.

General statement.—It must be continually borne in mind that absolute determination of the possibilities of occurrence or nonoccurrence of oil in any one locality, by work on the surface, even when augmented by a study of the known underground conditions in developed territory, is not possible. The best that can be done is to calculate the degree of probability on the basis of a summation of indications and structural conditions. The following conclusions concerning the prospects of the Summerland district are offered simply as the personal opinion of the writer after a study of this district.

Summerland field proper.—As regards the region immediately about Summerland, it is quite evident that the limits of the productive territory for wells of moderate depth, say up to 600 feet, have been pretty well outlined. The question for this territory seems to be more one of transportation facilities, markets, and cooperation among the operators than of unknown possibilities of development. There is certainly considerable territory between the Becker and Duquesne wharves, not to mention other undrilled territory in the northern part of the field, that should yield good returns for the cost and care of wells if the price of oil was what it was a few years ago. Until the price rises or

[a] Bull. California State Mining Bureau No. 19, 1900, p. 105.

[b] As this well was not being operated in October, 1906, it is assumed that it was a failure.—R. A.

until cheaper transportation rates are obtained, however, it seems useless to carry on further development.

The conditions of structure do not appear to favor the probability of striking remunerative deposits of oil by deep drilling. It is true that oil would probably be encountered in wells 2,000 or more feet in depth put down almost anywhere over the territory underlain by the Monterey shale, but the steep dips and close texture of the shale apparently preclude the accumulation of such great deposits of oil as are found in fields where the rocks are less steeply inclined and more porous.

Region near Carpinteria.—The last paragraph is as applicable to the region about Carpinteria and to the east as far as the contorted condition of the shale extends as it is to that territory about Summerland which is underlain by the Monterey. More or less oil is inclosed in the shale and in local interbedded sandstones, but it does not appear likely that heavy producers will ever be encountered in a region of such distortion and fracturing as is prevalent in the Monterey shale all along this part of the coast, although in certain facies of the shale fracturing seems to be essential to the migration of the oil within or through it.

Region west of Montecito.—It is thought that wells sunk deep enough to penetrate the basal beds of the Fernando formation in the region of the Montecito anticline (see Pl. I, p. 18), which extends indefinitely west-northwestward from the coast 1 mile west of Montecito Landing, will strike deposits of oil of about the same quality as the best of that encountered at Summerland.

Region of the Topatopa formation (Eocene) northeast of Summerland.—In the light of the development which has already taken place in Toro, Oil, Santa Monica, and Arroyo Parida canyons it seems almost certain that light producers (averaging from 2 to 6 or 8 barrels a day of 14° to 18° oil), 1,000 feet or less in depth, could be put down at many places along the contact between the upper Topatopa shale and sandstone zones or the contact between the Topatopa and Sespe formations in the region northeast of Summerland. The oil-bearing strata in both of these belts are apparently confined to the upper part of the Topatopa, and to obtain productive wells is simply a question of locating places where the structure appears most advantageous for the accumulation of the petroleum. The region near the Arroyo Parida fault, toward the east end of the area covered by the map, appears promising, although the wells here, especially on the north side of the fault, would have to go much deeper to strike the oil zone than they do at the tested localities.

PHYSICAL AND CHEMICAL PROPERTIES OF THE OIL.

PHYSICAL PROPERTIES.

COLOR.

Nearly all of the oil in the Summerland field is dark brown or black. The exceptions to this are the olive-brown oil from some of the Becker and Potomac wells, at the north end of the field, and a heavy dark green oil from the Fischer dug well, near Loon Point. The oil from the wells penetrating the Monterey shale (middle Miocene), in the vicinity of Carpinteria and farther east is black, as is also that from the Occidental wells sunk in the Topatopa formation (Eocene) in Toro Canyon. An amber-colored petroleum is reported from the Santa Monica Oil Company's well in the Topatopa sandstone north of Carpinteria.

GRAVITY.

The gravity of the oil from the Summerland field ranges from 9° to 18° Baumé, the average being between 14° and 15°. The Summerland oil and that from certain portions of the Los Angeles district are the heaviest of the California oils. The oil from the Monterey shale in the region about Carpinteria and Rincon ranges from liquid asphalt (gravity, about 9° Baumé) to the 20° petroleum from the Rincon well. It is claimed that oil of 37° gravity is found in the Columbia Oil and Asphalt Company's well at Carpinteria, but none of this light oil was seen by the writer. The gravity of the oil from the Occidental wells (in the Topatopa formation) is said to be 17° when it first comes from the wells, but to fall soon to 14° on exposure to the air. The same formation yields 18° oil in the Santa Monica well north of Carpinteria.

The lightest oil in the Summerland field is found in the main sand (A), in the beds of steepest dip at the north end of the field; in proximity to the local anticline or fault in the Potomac wells, also at the north end; in the Miller and Williams wells near the axis of the Loon Point anticline, at the east end; and in the second and third sands in the region of the Duquesne wharves. The heaviest oil comes from some of the beach and bluff wells between the North Star and Treadwell wharves. In general, the oil in any bed improves in quality down the dip, although in the Sea Cliff wells the opposite is said to be true. Water in the wells south of the railroad is believed to account for the lower gravity of the oil from this area as compared to that from the almost water-free oil sands north of the track.

The following table gives the details of the gravity of the oil in the different parts of the Summerland field:

Gravity of the oil from different parts of the Summerland field.

	° Baumé.
North of railroad track	13-14
Average	nearly 14
Eureka Oil Company's wells	14
Extreme northeast corner of field (Potomac wells)	15
Between railroad and beach	9-15½
Average	13
Santa Barbara Oil and Mining Company's wells	9-13
Wilson wells	13½
California Oil Company's wells	12-13
Miller and Williams wells (extreme east end)	15½
Beach and wharf wells	12-18
Average	15
Williams No. 2 beach well	18
Becker wells	16-17
North Star wells	13-15
Oxnard wells, upper sand	14
Oxnard wells, lower sand	15½
Sea Cliff wells, upper sand, beach	14
Sea Cliff wells, upper sand, wharf	13
Western Duquesne wharf wells, upper sand	14
Western Duquesne wharf wells, middle sand	16
Western Duquesne wharf wells, lower sand "rock"	17½

VISCOSITY.

The relative viscosity of the Summerland oils as compared with that of oils from other typical California fields is given in the table of chemical analyses on page 62.

CHEMICAL PROPERTIES.

GENERAL STATEMENT.

For data concerning the chemical properties of the Summerland oil, the writer is indebted entirely to persons outside of the Geological Survey, as up to the present time this Bureau has undertaken no detailed chemical investigations of petroleums. The following, among others, have contributed to the present knowledge of the California petroleums, and to them the writer wishes to acknowledge his indebtedness for the analyses contained in the succeeding pages: Messrs. W. L. Watts,[a] S. F. Peckham,[b] Charles F. Mabery,[c] Clifford Richardson,[d] Paul W. Prutzman,[e] H. N. Cooper,[f] and Edmond O'Neill.[g]

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[a] Bull. California State Mining Bureau No. 11, 1897, pp. 67-69. No. 19, 1900, p. 203.
[b] See Bull. U. S. Geol. Survey No. 309, 1907, p. 201, for complete list of this writer's papers relating to California petroleum.
[c] Proc. Am. Acad. Arts and Sci., vol. 36, 1901, pp. 255-283; vol. 40, 1904, pp. 340-346.
[d] Jour. Franklin Inst., vol. 162, 1906, pp. 57-70, 81-128.
[e] Bull. California State Mining Bureau No. 32, 1904, pp. 184, 194, 198, 224, etc.
[f] Bull. California State Mining Bureau No. 31, 1904, No. 32, 1904, opp. p. 230.
[g] Jour. Am. Chem. Soc., vol. 25, 1903, pp. 707-709.

The most prominent characteristics of the Summerland oil are its low gravity (12° to 16° Baumé), its high percentage of asphalt (85.5 per cent,[a] the highest of all the California oils), its relatively high percentage of nitrogen (1.25 per cent[b]), and its moderately low sulphur content (0.84 per cent[b]).

RICHARDSON'S PAPER.

The most comprehensive yet condensed discussion of the chemical properties of the Summerland oil is that by Clifford Richardson in his "Petroleum of North America."[c] That part of his paper which relates to the Summerland oil is here given in its entirety, as introductory to the tables of analyses which follow. Richardson says:

A specimen of the dense Summerland oil collected by the writer and distilled in vacuo at a pressure of 26 mm. gave 55 per cent of distillate, which was collected in 15 fractions, having the following specific gravity at 20°:

1	0.8712	9	0.9618
2	.8833	10	.9678
3	.8893	11	.9738
4	.9034	12	.9802
5	.9155	13	.9830
6	.9336	14	.9900
7	.9417	15 (refractive index, 1.542)	.9939
8	.9477		

Residue (45 per cent), a hard asphalt. Penetration, 66.

The highest boiling fraction has a density very nearly that of water and a refractive index of 1.542. The residue consisted of a hard residual pitch. On redistilling the first fraction at the same pressure, distillates began to come over at 105°, having a specific gravity of 0.8460, 35.5° B., and a refractive index of 1.460. Paraffin scale could not be separated from any of the fractions on exposing them to an extremely low temperature.

Mabery [d] has examined this oil in considerable detail. He found that a sample which he obtained, having a specific gravity of 0.9845, 12.2° B., had the following ultimate composition:

Carbon	86.32
Hydrogen	11.70
Nitrogen	1.25
Sulphur	.84
	100.11

His distillates were of a character similar to those found by the writer. He continued his fractionation until heaps were obtained at certain temperatures. After purification with sulphuric acid and caustic soda he examined the saturated hydrocarbons thus obtained with the following results:

[a] Prutzman, P. W., Bull. California State Mining Bureau No. 32, 1904, p. 184.
[b] Mabery, C. F., Proc. Am. Acad. Arts and Sci., vol. 40, 1904, p. 341.
[c] Jour. Franklin Inst., vol. 162, 1906, pp. 57-70, 81-128.
[d] Proc. Am. Acad. Arts and Sci., vol. 40, 1904, p. 340.

Hydrocarbons separated from Santa Barbara (Cal.) petroleum.

Symbol.	Boiling point.		Specific gravity at 20°.	Refractive index.
	Degrees.	*Millimeters*		
$C_{13}H_{24}$	150–155	60	0.8621	1.4687
$C_{16}H_{30}$	175–180	60	.8808	1.4700
$C_{17}H_{30}$	190–195	60	.8919	1.4778
$C_{18}H_{32}$	210–215	60	.8996	1.4814
$C_{24}H_{44}$	250–255	60	.9299	....
$C_{27}H_{46}$	310–315	60	.9451	1.5146
$C_{29}H_{50}$	340–345	60	.9778	....

The most volatile of these fractions belong to the C_nH_{2n-2} series. With the third the series becomes C_nH_{2n-4}, and with the sixth C_nH_{2n-8}, the density of the last fraction and its boiling point being extremely high. A hydrocarbon of the C_nH_{2n-2} series, of very similar molecular weight, has also been separated by the writer from Trinidad asphalt and found to have the following physical characteristics:

Boiling point	147°–170° at 30 mm.
Specific gravity	0.8576
Baumé	33.20
Refractive index	1.465
Carbon	86.85 per cent.
Hydrogen	13.34 per cent.

The resemblance between the physical properties and ultimate composition of these fractions with some of those obtained by Mabery renders it probable that the same series are present in Trinidad asphalt as in California oil. The latter oil is without doubt extremely asphaltic in nature, as is evident from the fact that it leaves 45 per cent of hard pitch, resembling asphalt, on distillation in vacuo.

On distillation with steam of the sludge obtained from treating the above distillates with strong sulphuric acid, the sulphur derivatives of the petroleum, the presence of which is shown by the ultimate analysis, have been recovered by the writer and found to correspond to those obtained in Canadian oil.

On treatment of the distillates with dilute sulphuric acid, one to four, the nitrogen derivatives, the presence of which is also shown by the ultimate analysis, can be recovered. They are probably hydroquinolenes. Their examination has been undertaken by Mabery.[a] He finds that fractions of the nitrogenous oil, separated by repeated distillation, have the following composition:

130°–340°	$C_{12}H_{17}N$	223°–225°	$C_{15}H_{19}N$
197°–199°	$C_{13}H_{18}N$	243°–245°	$C_{16}H_{19}N$
215°–217°	$C_{14}H_{19}N$	270°–275°	$C_{17}H_{21}N$

ANALYSES.

The subjoined analyses of two Summerland oils, to which have been added for comparison the analyses of typical oils from other California districts, show the general character of the petroleums under discussion. This table is followed by several others showing the results of various analyses and distillation tests, which are useful as indicating the properties of the Summerland oils.

[a] Jour. Soc. Chem. Ind., vol. 19. 1900, p. 505.

Chemical analyses of California petroleum.[a]

[By H. N. Cooper, chemist. Data and samples collected by Marion Aubury, field assistant.]

Number.	Name of company.	County.	District.	Gravity (° B.).	Specific gravity of crude at 15° C. (about 60° F.).	Flash (degrees).	Viscosity. At 15° C. (59° F.). Seconds.	Viscosity. At 15° C. (59° F.). Seconds ÷ 27½ or water=1.	Viscosity. At 85° C. (185° F.). Seconds.	Viscosity. At 85° C. (185° F.). Seconds ÷ 27½ or water=1.	Sulphur (per cent).	Calorific value of dry sample.[b]	Calorific values per cubic centimeter.
1	Sea Cliff Oil Co.	Santa Barbara	Summerland	14.9	0.9665	+70	+1,800	+65	108	3.91	0.44	10,348	10,001
2	Potomac Oil Co.	do.	do.	15.8	.9603	+70	+1,800	+65	90½	3.20	....	....	....
3	Alameda Oil Co.	Kern	Sunset	12.6	.9816	44	+1,800	+65	82½	2.99	.90	10,364	10,173
4	Buckhorn Oil and Trans. Co.	Ventura	Buckhorn	14.6	.9685	+70	+1,800	+65	116	4.20	....	....	....
5	Union Oil Co. of California	Santa Barbara	Lompoc	16.2	.9574	21	+1,800	+65	227	8.23	4.43	10,258	9,822
6	Davis & Harrison	Los Angeles	Eastern field	17.9	.9467	+70	1,700	61.59	55	1.99	....	....	....
7	Santa Fe Co.	Orange	Fullerton	19.	.9399	44	1,790	64.85	71	2.57	1.09	10,441	9,813
8	Home Oil Co.	Los Angeles	Whittier	20.7	.9291	26	393	14.24	43	1.56	....	....	....
9	California Oilfields Co. (Ltd.)	Fresno	Coalinga	23.	.9150	-15	172	6.23	37	1.34	.45	10,629	9,726
10	Pinal Oil Co.	Santa Barbara		27.6	.8882	-15	90	3.27	37¾	1.36	1.56	10,543	9,364
11	Puente Oil Co.	Los Angeles	Puente	29.5	.8775	-15	66½	2.35	34	1.23	.36	10,699	9,389
12	Los Angeles Pacific Rwy. Co.	Ventura	Timber Canyon	35.1	.8481	-15	45½	1.66	31½	1.13	....	....	....
13	Pacific Coast Oil Co.	Los Angeles	Pico Canyon	37.3	.8367	-15	38½	1.40	29½	1.07	.28	11,141	9,322

Distillation.

Number.	Percentage. Water.	Percentage. Up to 100° C.	Percentage. 100°-150° C.	Percentage. 150°-200° C.	Percentage. 200°-250° C.	Percentage. 250°-300° C.	Percentage. 300° C. to asphalt. A.	Percentage. 300° C. to asphalt. B.	Percentage. Asphalt.	Percentage. Loss or gain.	Specific gravity of preceding fractions at 15° C. (about 60° F.). Up to 100° C.	Sp. gr. 100°-150° C.	Sp. gr. 150°-200° C.	Sp. gr. 200°-250° C.	Sp. gr. 250°-300° C.	Sp. gr. 300° C. to asphalt. A.	Sp. gr. 300° C. to asphalt. B.
1	0.7	0	0	1	10	17.4	45.5	....	23.5	-1.9	....	....	....	0.8516	0.8840	0.9347	....
2	Trace.	0	0	3	9.9	15.4	48	....	22.8	-.9	....	....	0.8082	.8535	.8913	.9143	....
3	None.	0	0	10.6	8.7	24.3	28.7	5.8	23.5	+1.6	....	....	.8192	.8731	.9070	.9113	0.9193
4	9.3	0	0	5.9	15.3	6	23.7	16.7	23	-.1	....	....	.8607	.8888	....	.9156	.9307
5	7	1.3	3.9	5.5	7.7	18.3	34.3	....	20.6	-1.4	....	0.7737	.7906	.8316	.8613	.8992	....
6	2	0	0	0	6.6	17.5	47.8	9.8	17.3	-.8	....	....	....	.8568	.8855	.9099	.9094
7	1.3	0	0	11.2	10.5	15.5	28.3	9.9	23.1	-.2	....	....	.8113	.8551	.8850	.8857	.9001
8	None.	0	4.2	9.6	14	14.7	23	16.8	15.7	-2	....	.7756	.8313	.8672	.8991	.9210	.9166
9	None.	.2	5.5	7.5	10.6	16	43	4.2	11.6	-1.4	....	.7716	.8125	.8494	.8855	.8983	.9358
10	None.	8.2	17.7	12.1	9.4	9.1	29.7	....	12	-1.8	0.7123	.7617	.8132	.8583	.8899	.9085	....
11	None.	8	15.4	9	10.1	14	23.1	5.7	13.1	-1.6	.7265	.7720	.8155	.8413	.8648	.8862	.8837
12	None.	15.3	15	9.5	9.9	9.9	28	....	10.6	-1.8	.7002	.7639	.8015	.8321	.8624	.8875	....
13	None.	10.5	20.4	13.8	13	11.1	16.9	6.8	6.8	-.7	.7472	.7659	.8040	.8350	.8606	.8870	.8720

[a] Part of Bull. California State Mining Bureau No. 31, 1904. For an explanation of the methods used in these analyses, see Bull. U. S. Geol. Survey No. 309, 1907, pp. 205-208, or Bull. California State Mining Bureau No. 31; No. 32, p. 231.

[b] To convert calories into British thermal units, multiply by 1.8.

Fractional distillations of five Summerland oils and four other California oils.

[By W. L. Watts, Bull. California State Mining Bureau No. 11, 1897, pp. 67-69.]

Source of oil.	Crude oil.		Naphtha. 150° C.			Illuminating oil. 200° C.		
	Specific gravity.	Nearest corresponding degree, Baumé.	Volumetric percentage of distillate cut off.	Specific gravity.	Nearest corresponding degree, Baumé.	Volumetric percentage of distillate cut off.	Specific gravity.	Nearest corresponding degree, Baumé.
Summerland	0.9672	15	Tr.	....	....	Tr.	....	....
Do	.9513	17	Tr.	....	....	Tr.	....	....
Do	.9657	15	Tr.	....	....	Tr.	....	....
Do	.9672	15	Tr.	....	....	Tr.	....	....
Do	.9692	15	Tr.	....	....	Tr.	....	....
Second Street Park, Los Angeles	.9534	17	Tr.	....	....	Tr.	....	....
Silverthread district, Ventura County	.9255	21	7	0.7428	59	10.4	0.7614	54
Kentuck wells, Ventura County	.9015	25	6	.7200	64	8.6	.7600	54
Puente district, Los Angeles County	.8893	28	10.2	.7323	61	13.5	.7656	53

Source of oil.	Illuminating oil. 250° C.			Illuminating oil. 300° C.			Lubricating oil. 350° C.		
	Volumetric percentage of distillate cut off.	Specific gravity.	Nearest corresponding degree, Baumé.	Volumetric percentage of distillate cut off.	Specific gravity.	Nearest corresponding degree, Baumé.	Volumetric percentage of distillate cut off.	Specific gravity.	Nearest corresponding degree Baumé.
Summerland	Tr.	....	....	11	0.8452	36	5	0.8722	30
Do	Tr.	....	....	19.4	.8550	34	12	.8962	26
Do	Tr.	....	....	11.6	.8468	35	6.8	.8900	27
Do	Tr.	....	....	6	....	....	5	....	....
Do	Tr.	....	....	....	....	....	4.6	....	....
Second Street Park, Los Angeles	8	0.8330	38	13.6	.8653	32	3	....	....
Silverthread district, Ventura County	8	.8001	45	9.8	.8430	36	6.4	.8612	33
Kentuck wells, Ventura County	10	.8047	44	12.2	.8450	36	2.5	.8662	32
Puente district, Los Angeles County	12.2	.8089	43	10.2	.8413	36	8.3	.8502	34

Proximate analysis of a 15° Baumé Summerland oil.[a]

DISTILLATION.

	Per cent.	Gravity (° Baumé).		Per cent.	Gravity (° Baumé).
Below 150° C.	0	....	Asphalt	32	E.
150°-270° C.	10	35.4	Loss	3.8	....
Above 270° C.	54	22.2			

[a] Prutzman, P. W., Bull. California State Mining Bureau No. 32, 1904, p. 198.

CALCULATED ANALYSIS.

Total gasoline	0	40	Asphalt, volume	32.2	....
Kerosene	3	40	Asphalt, weight (117.3 pounds per barrel)	35	....
Middlings	28.5	33.4	Loss	3.8	....
Lubricants	40.5	18			

Proximate analysis of a Summerland oil.[a]

Specific gravity at 21° C	0.9815
Corresponding degree Baumé	12.7
Specific viscosity at 15½° C. (60° F.)	1,462.83
Specific viscosity at 85° C. (185° F.)	8.35
Fractional distillation:	
Water ... per cent	25.00
Below 100° C. (212° F.) ... do	.00
100°-150° C. (212°-302° F.) ... do	.00
150°-250° C. (302°-482° F.) ... do	6.50
250°-350° C. (482°-662° F.) ... do	17.10
350° C. (662° F.) to asphalt ... do	27.50
Asphalt ... do	22.50
Loss ... do	1.40

Distillation test of 14° Baumé (tank average) Summerland oil.[b]

Engine distillate (48°)	0.1
Kerosene (41°)	3.0
Stove oil (33°)	4.0
Gas oil (28°)	16.3
Fuel distillate (25°)	19.1
Lubricants (21.5°)	20.4
Asphalt (grade D)	37.1
	100.0

Sample slightly heavier than the average oil of the Summerland district.

Incidental constituents of Summerland crude oil.[c]

Constituents.	Gravity (° Baumé).	Per cent.
Nitrogen		0.880
Sulphur	15	.898
Asphaltene	15	3.36

TECHNOLOGY AND PRODUCTION.

COST OF DRILLING WELLS AND PRODUCING THE OIL.

Cost of drilling.—The cost of drilling in the Summerland field is not great, owing to the shallowness of the wells and the softness of the strata overlying the oil sands. Watts[d] is authority for the statement that the cost of drilling, exclusive of the cost of the casing, averages about $1 a foot. The following statement shows the detailed cost (exclusive of the wharf) of two wharf wells near the east end of the field:

Cost of 225-foot well, Summerland.

1 length 7⅝-inch casing	$20.00
150 feet 5⅝-inch casing, at 60 cents	90.00
225 feet 4¼-inch casing, at 40 cents	90.00

[a] O'Neill, Edmond, Jour. Am. Chem. Soc., vol. 25, 1903, pp. 707-709.
[b] Prutzman, P. W., Bull. California State Mining Bureau No. 32, 1904, p. 191.
[c] Prutzman, P. W., Bull. California State Mining Bureau No. 32, 1904, p. 224.
[d] Bull. California State Mining Bureau No. 19, 1900, p. 103.

232 feet 2-inch tubing, at 23 cents	$53.36
Drilling 230 feet, at 80 cents	184.00
Derrick	12.00
Shoes, $5 and $6.50	11.50
Pump	18.00
Sucker rods, at $6.20 per hundred feet	14.50
	493.36

Cost of 250-foot well, Summerland.

Conductor, 9⅝-inch, 20 feet	$30.00
Casing, 250 feet; 7⅝-inch	250.00
Casing, about 250 feet, 2-inch pipe, at 23 cents	59.11
Drilling 250 feet, at 85 cents (about)	217.50
Derrick	12.00
Shoe	9.00
Pump	18.00
Sucker rods	15.90
	611.51

Cost of producing the oil.—The cost of production varies throughout the field, owing to the variations in the yield of each well, in the quantity of water and sand that is pumped with the oil, etc. In general, however, the cost ranges from 25 to 30 cents a barrel, although it is said to be as high as 40 cents in some of the wells.

SEPARATION OF SAND AND WATER FROM OIL.

The separation of the sand from the oil is accomplished by means of a "sand box," into which the oil is run and in which a large portion of the sand settles. The "sand box" consists of a wooden trough divided by two or more upright partitions that run across it. At the top of the partitions are notches through which the oil passes, and the sand is deposited at the bottom. The oil is run into a tank, at the bottom of which a space of 10 inches or more is allowed for any sand which may still be in it.

Heat accelerates the separation of the water from the oil, and in order to apply it to the emulsion which comes from the pumps, the emulsion is allowed to stand for about twelve hours in tanks containing coils of steam pipes. In these tanks the water settles to the bottom while the oil rises to the top, and each is conveyed separately from the tank. As a substitute for the heating tank one operator heats his oil in its passage from the wells to the settling tanks by passing it through three turns of pipe in a steam-heated chamber consisting of 20 feet of large casing. The chamber is heated by steam from the pump exhaust.

PRODUCTION.

The total production of the Summerland field from 1895 to January 1, 1907, exclusive of 1896, was 1,373,980 barrels. The field reached its maximum yield in 1899, when it produced 208,370 barrels of crude petroleum. Since that time the yield has been gradually falling off on account of the natural decline in production of the individual wells and the cessation of drilling operations, and also because of adverse market and transportation facilities. In the early history of the field three to five year contracts for 90 cents a barrel were obtainable; now the producers can barely get enough to cover the cost of production.

The following table shows the production by years from 1895 to 1906, inclusive.

Production of the Summerland field.[a]

[Barrels of 42 gallons.]

1895	16,904	1902	143,552
1896	....	1903	127,926
1897	130,136	1904	119,506
1898	132,217	1905	123,871
1899	208,370	1906	81,848
1900	153,750		
1901	135,900		1,373,980

UTILIZATION AND TRANSPORTATION.

Most of the oil now produced in this field, with the exception of that coming from the Southern Pacific Company's wells, is used locally, either in the Summerland refinery or for oiling roads or for fuel in the vicinity of Santa Barbara. At one time much of the oil was shipped to Los Angeles and elsewhere over the Southern Pacific Railroad, but a combination of high freight rates with a poor market has practically stopped exportation.

REFINERY.

One refinery, that of the California Liquid Aspnalt Company, is located at Summerland. It is equipped with two stills and has a still capacity of 300 barrels of crude oil. Summerland oil is used entirely, distillates and asphalt being the products. A higher percentage of asphalt is derived from the oil from this field than is found in any of the other California oils.

The following companies were engaged in the production of oil at Summerland January 1, 1907:

[a] With the exception of the figures for 1895, which are from Bull. California State Mining Bureau No. 11, 1897, p. 57, the figures of production were furnished by the division of mining and mineral resources, U. S. Geol. Survey.

COMPANIES NOW OPERATING.

G. F. Becker Oil Company.
Knapp & Hassinger (Royal Oil Company).
J. C. Lillis.
Lillis Oil Company.
Montecito Improvement Company.
Miller & McFarland.
North Star Oil Company (J. C. Lillis).
Oxnard Oil Company.
Potomac Oil Company.
Sea Cliff Oil Company.
Sea Side Oil Company.
Southern Pacific Railroad Company (Kern Trading and Oil Company).
Sunset Oil Company.
J. C. Wilson.

PLATES IX TO XVII.

PLATE IX.

TOPATOPA (EOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.)

FIG. 1. *Meretrix uvasana* Conrad. Pal. California, vol. 1, 1864, pl. 30, fig. 248. Right valve; longitude, 55 mm. A common species in the Eocene.

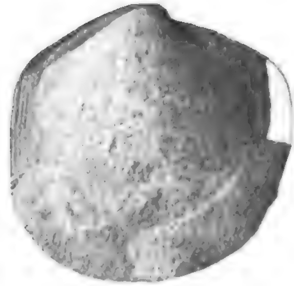
FIG. 2. *Ostrea idriaensis* Gabb, type. Pal. California, vol. 2, 1868, pl. 34, fig. 103. Exterior of right valve; altitude, 58 mm. A common species in the Eocene of the Santa Cruz Mountains.

FIG. 3. *Venericardia planicosta* Lamarck, U.S.N.M. 164973. Left valve; longitude, 84 mm. Eocene, Little Falls, Wash. This is the most widespread and characteristic Eocene species in the world.

FIG. 4. *Phacoides cretacea* Gabb, U.S.N.M. 165254. Cast of right valve of a medium-sized specimen; altitude, 18 mm.; view of exterior, × 2. Topatopa formation near head of West Fork of Sycamore Canyon, Santa Barbara.

FIG. 5. *Cardium brewerii* Gabb, type. Right valve; altitude, 61 mm.; view of exterior natural size. Pal. California, vol. 1, 1864, pl. 24, fig. 155. A common species in the Eocene of the Santa Ynez Mountains.

1



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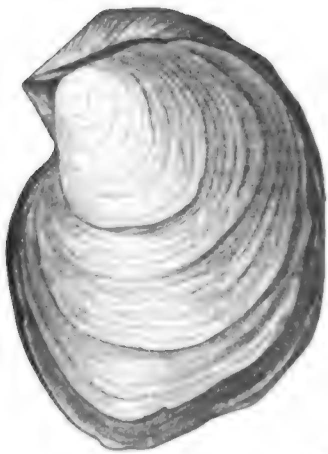

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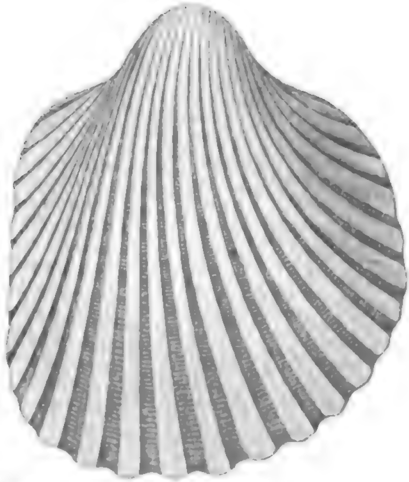

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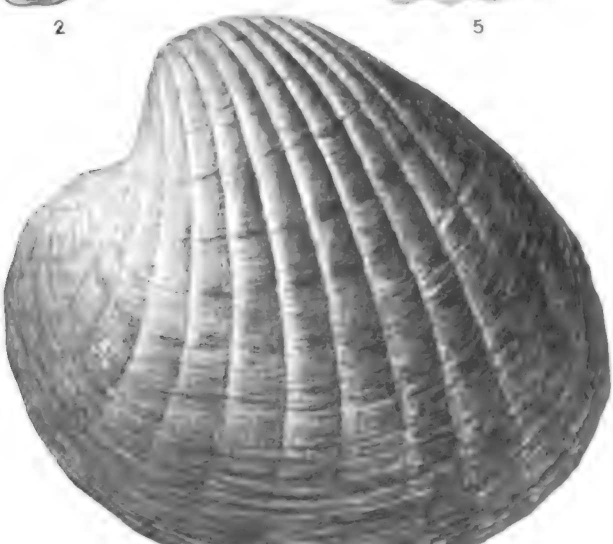

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TOPATOPA (EOCENE) FOSSILS.

PLATE X.

TOPATOPA (EOCENE) AND MONTEREY (MIOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.

FIG. 1. *Leda gabbi* Conrad. Pal. California, vol. 1, 1864, pl. 26, fig. 185. Longitude, 18 mm.; enlarged. A common species in the Eocene.

FIG. 2. *Fusus occidentalis* Gabb, type. Altitude, 15 mm.; back view, × 2½. Pal. California, vol. 2, 1868, pl. 26, fig. 23. Abundant in the Eocene of the Santa Ynez Range.

FIG. 3a. *Galerus excentricus* Gabb, U.S.N.M. 165258. Internal cast of a fairly representative specimen; altitude, 14 mm.; view of side, × 2. Topatopa formation, near head of West Fork of Sycamore Canyon, Santa Barbara.

FIG. 3b. View of top of same specimen, × 2.

FIG. 4. *Modiolus ornatus* Gabb. Right valve; longitude, 38 mm. Pal. California, vol. 1, 1864, pl. 24, fig. 166. A common species in the California Eocene.

FIG. 5. *Meretrix uvasana* Conrad, U.S.N.M. 165253. Cast of right valve of a young specimen; longitude, 15 mm.; view of exterior, × 2. Topatopa formation, near head of West Fork of Sycamore Canyon, Santa Barbara.

FIG. 6. *Mactra* near *ashburnerii* Gabb, U. S. N. M. 165257. An internal cast of left valve; longitude, 20 mm.; view of front, × 2. Topatopa formation, near head of West Fork of Sycamore Canyon, Santa Barbara.

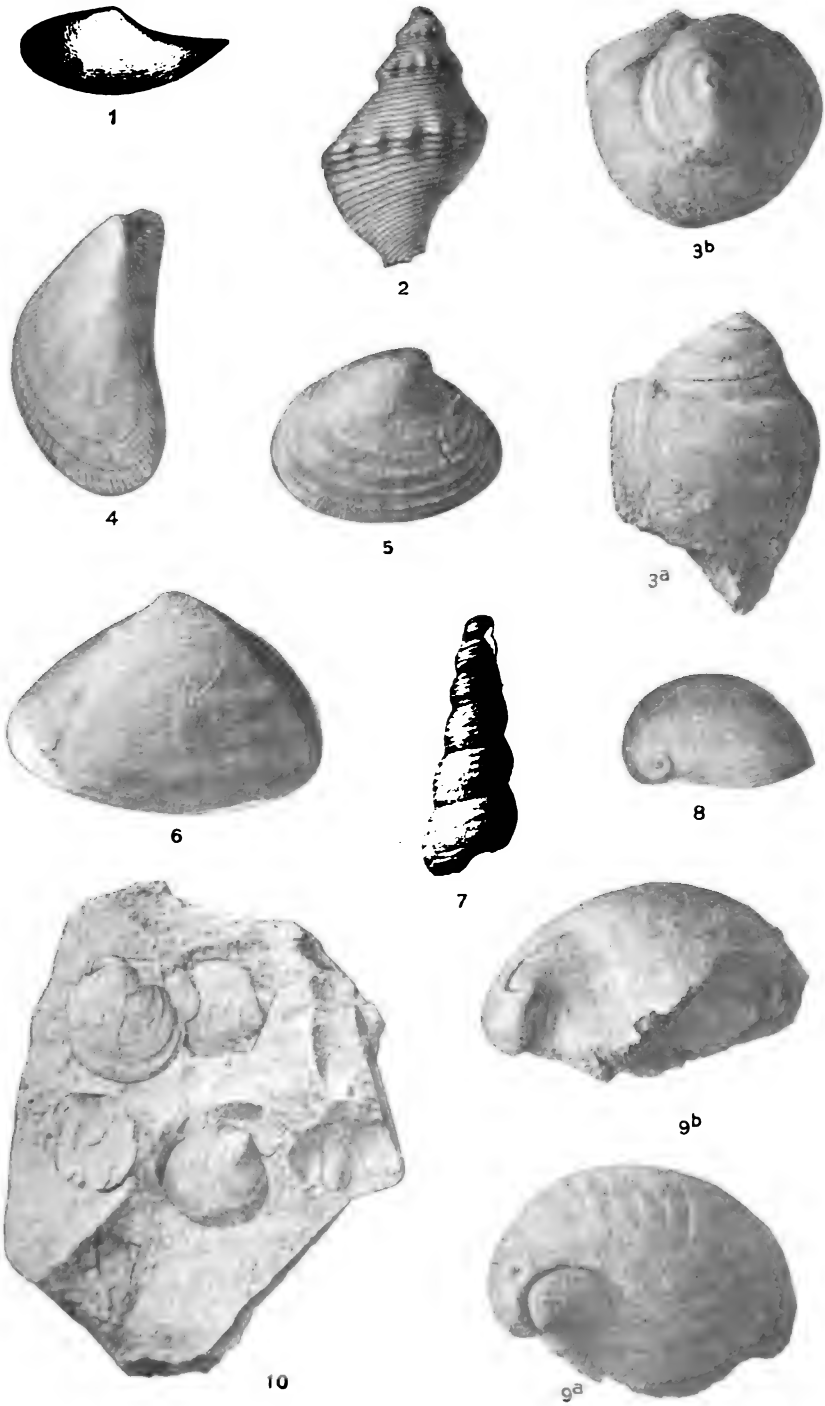
FIG. 7. *Turritella uvasana* Conrad, U. S. N. M. 165255. An imperfect cast; altitude, 33 mm. Topatopa formation, near head of West Fork of Sycamore Canyon, Santa Barbara.

FIG. 8. *Spirocrypta pileum* Gabb. Pal. California, vol. 1, 1864, pl. 29, fig. 233. Longitude, 13.5 mm.; view of side, enlarged. A common form in the Eocene.

FIG. 9a. *Spirocrypta pileum* Gabb, U. S. N. M. 165256. Internal cast; longitude, 22 mm.; view of top × 2. Topatopa formation, near head of West Fork of Sycamore Canyon, Santa Barbara.

FIG. 9b. View of side of same specimen, × 2.

FIG. 10. *Pecten peckhami* Gabb, U. S. N. M. 164839. Cast of right and left valves in matrix. Monterey shale (middle Miocene), southeast of Pinole, Contra Costa County, Cal. A common species in the Monterey shale of the Coast Range.



TOPATOPA (EOCENE) AND MONTEREY (MIOCENE) FOSSILS.

PLATE XI.

FERNANDO (PLIOCENE) GASTEROPODA.

(All specimens are from Fernando formation, Bath-house Beach, Santa Barbara. Unless otherwise indicated, all figures are natural size.)

FIG. 1. *Mitramorpha filosa* Carpenter, var. *barbarensis* Arnold, U. S. N. M. 165245 (type). Altitude, 6.5 mm.; aperture view, × 4. Characteristic of this horizon.

FIG. 2. *Lacuna compacta* Carpenter, U. S. N. M. 165235. Altitude, 6.5 mm.; aperture view, × 4. Also known recent.

FIG. 3. *Leptothyra bacula* Carpenter, U. S. N. M. 165236. Diameter, 3 mm.; aperture view, × 6. Also known recent.

FIG. 4. *Mangilia tabulata* Carpenter, U. S. N. M. 165240. Altitude, 4 mm.; aperture view, × 4. Also known recent.

FIG. 5*a*. *Puncturella delosi* Arnold, U. S. N. M. 165234 (type). Altitude, 1.9 mm.; view of side, × 10. Characteristic of this horizon.

FIG. 5*b*. Rear view of same specimen, × 10.

FIG. 6. *Tornatina culcitella* Gould, U. S. N. M. 165239. Altitude, 5 mm.; aperture view, × 4. Also known recent.

FIG. 7. *Amphissa corrugata* Reeve, U. S. N. M. 165243. Altitude, 11 mm.; aperture view, × 3. Also known recent.

FIG. 8. *Nassa perpinguis* Hinds, U. S. N. M. 165237. Altitude, 10 mm.; aperture view, × 2. Also known recent.

FIG. 9. *Clathurella conradiana* Gabb, U. S. N. M. 165247. Altitude, 11 mm.; aperture view, × 3. Also reported as recent, but the recent form is probably another species or variety.

FIG. 10. *Columbella* (*Astyris*) *tuberosa* Carpenter, U. S. N. M. 165242. Altitude, 9 mm.; aperture view, × 3. Also known recent.

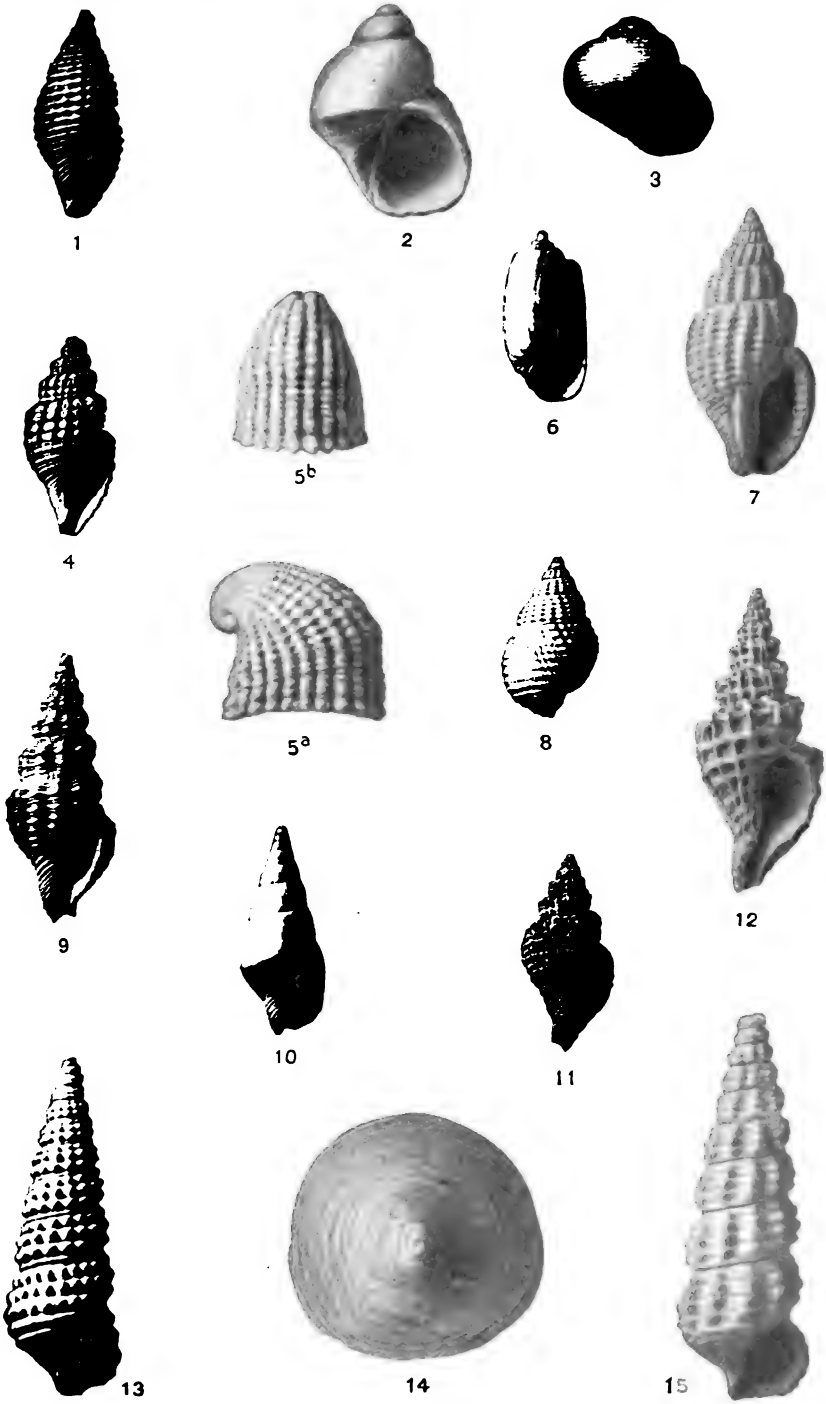
FIG. 11. *Ocinebra lurida* Middendorf, U. S. N. M. 165233. Altitude, 12 mm.; aperture view, × 2. Also known recent.

FIG. 12. *Trophon* (*Boreotrophon*) *stuarti* Smith, U. S. N. M. 165244. Altitude, 20 mm.; aperture view, × 2. Also known recent.

FIG. 13. *Bittium catalinensis* Bartsch, U. S. N. M. 165232 (type). Altitude, 7 mm.; aperture view, × 6.

FIG. 14. *Galerus mammillaris* Broderip, U. S. N. M. 165251. Maximum diameter, 17 mm.; view of top, × 2. Also known recent.

FIG. 15. *Bittium barbarensis* Bartsch, U. S. N. M. 165231 (type). Altitude, 8.5 mm.; aperture view, × 6.



FERNANDO (PLIOCENE) GASTEROPODA.

PLATE XII.

Fernando (Pliocene) Pelecypoda and Brachiopoda.

(Unless otherwise stated, all specimens are from Fernando formation, Bath-house Beach, Santa Barbara. All figures not otherwise indicated are natural size.)

Fig. 1*a*. *Mercenaria perlaminosa* Conrad, U.S.N.M. 165252. Right valve; longitude 87 mm.; view of exterior. Characteristic of this horizon.

Fig. 1*b*. View of same specimen from front.

Fig. 1*c*. *Mercenaria perlaminosa* Gabb, U.S.N.M. 165288. Longitude of fragment, showing hinge of left valve, 56 mm. Characteristic of this horizon.

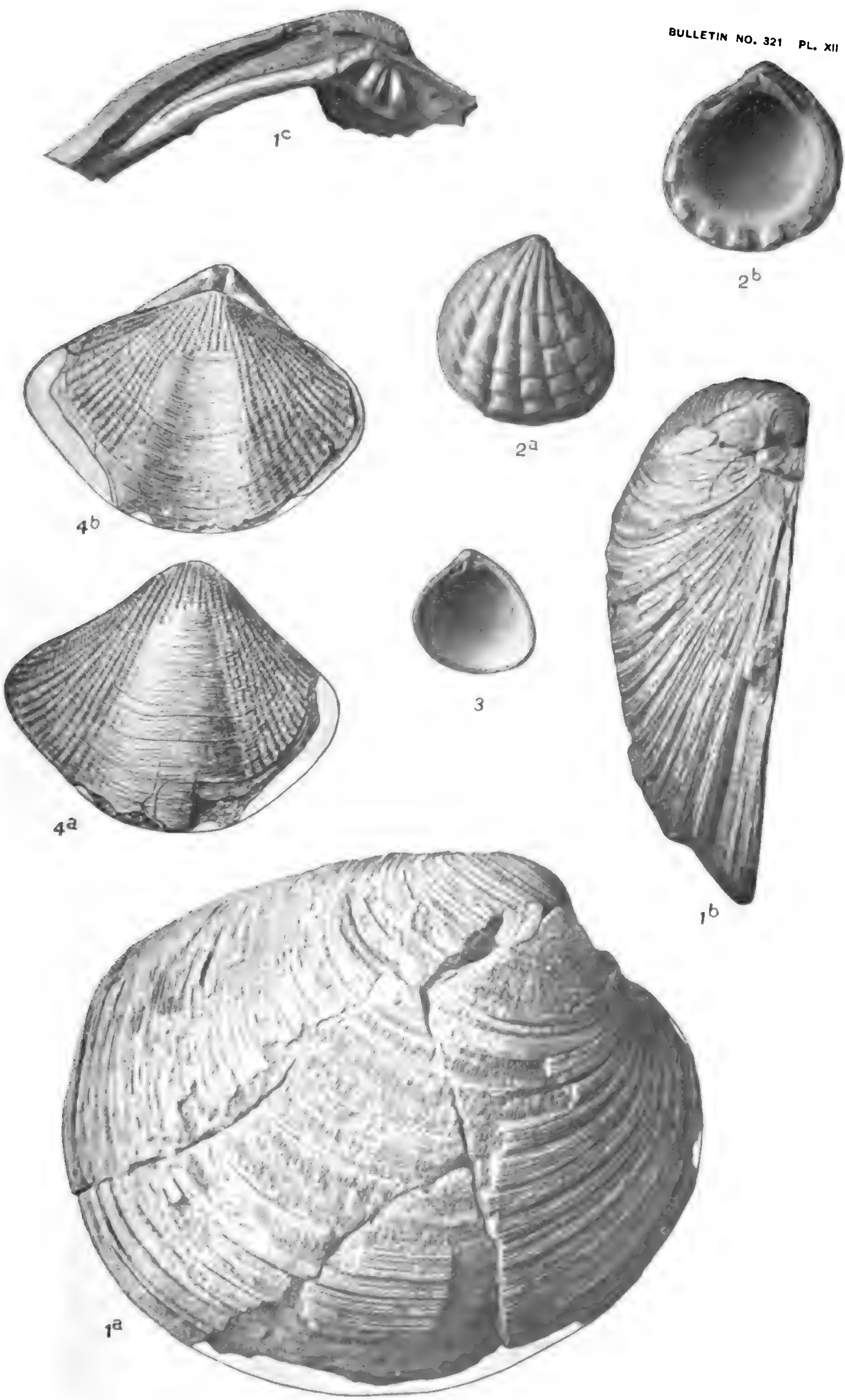
Fig. 2*a*. *Venericardia yatesi* Arnold, U.S.N.M. 165248 (type). Right valve; latitude 4 mm.; view of exterior, × 6. Characteristic of this horizon.

Fig. 2*b*. View of interior of same specimen.

Fig. 3. *Psephidia barbarensis* Arnold, U.S.N.M. 165238 (type). Altitude 4 mm.; view of interior, × 4. Characteristic of this horizon.

Fig. 4*a*. *Terebratalia hemphilli* Dall, U.S.N.M. 108495 (holotype). Proc. U. S. Nat. Mus., vol. 24, 1902, pl. 40, fig. 10. Ventral valve; longitude 35 mm.; view of exterior, slightly enlarged. Arroyo Burro, west of Santa Barbara.

Fig. 4*b*. Exterior of view of dorsal valve of same specimen. Op. cit., pl. 40, fig. 8.



FERNANDO (PLIOCENE) PELECYPODA AND BRACHIOPODA.

PLATE XIII.

FERNANDO (PLIOCENE) GASTEROPODA.

(Unless otherwise indicated, all figures are natural size.)

FIG. 1*a*. *Crepidula princeps* Conrad, U.S.N.M. 165315. Longitude 106 mm.; view of top. Packards Hill, Santa Barbara; characteristic of the Fernando in Santa Barbara County; also found in the Miocene and Pliocene elsewhere in the State.

FIG. 1*b*. Side view of same specimen.

FIG. 1*c*. Interior view of same specimen.

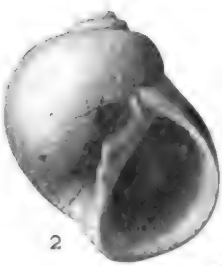
FIG. 2. *Natica clausa* Broderip and Sowerby, U.S.N.M. 165241. Altitude 7.5 mm.; aperture view, × 4. Fernando formation, Bath-house Beach, Santa Barbara. Also known recent.

FIG. 3. *Leptothyra paucicostata* Dall, U.S.N.M. 165246. Diameter 4 mm.; aperture view, × 6. Fernando formation, Bath-house Beach, Santa Barbara. Also known recent.

1c

3

1a



2

1b

FERNANDO (PLIOCENE) GASTEROPODA.

PLATE XIV.

FERNANDO (PLIOCENE) PELECYPODA.

(Unless otherwise indicated, all figures are natural size.)

FIG. 1. *Semele pulchra* Sowerby, var. *montereyi* Arnold, U.S.N.M. 165250. Right valve; latitude 18 mm.; view of exterior, × 2. Fernando formation, Santa Barbara. Also reported as recent.

FIG. 2. *Venericardia monilicosta* Gabb, U.S.N.M. 165249. Left valve; altitude 11 mm.; view of exterior, × 3. Fernando formation, Bath-house Beach, Santa Barbara. Characteristic of this horizon.

FIG. 3. *Pecten* (*Chlamys*) *opuntia* Dall, collection of Delos Arnold. Right valve; altitude 43 mm.; view of exterior. Same locality as fig. 4.

FIG. 4. *Pecten* (*Chlamys*) *opuntia* Dall, collection of Delos Arnold. Left valve; altitude 51 mm.; view of exterior. Fernando formation, Arroyo Burro, Santa Barbara. Characteristic of this horizon.

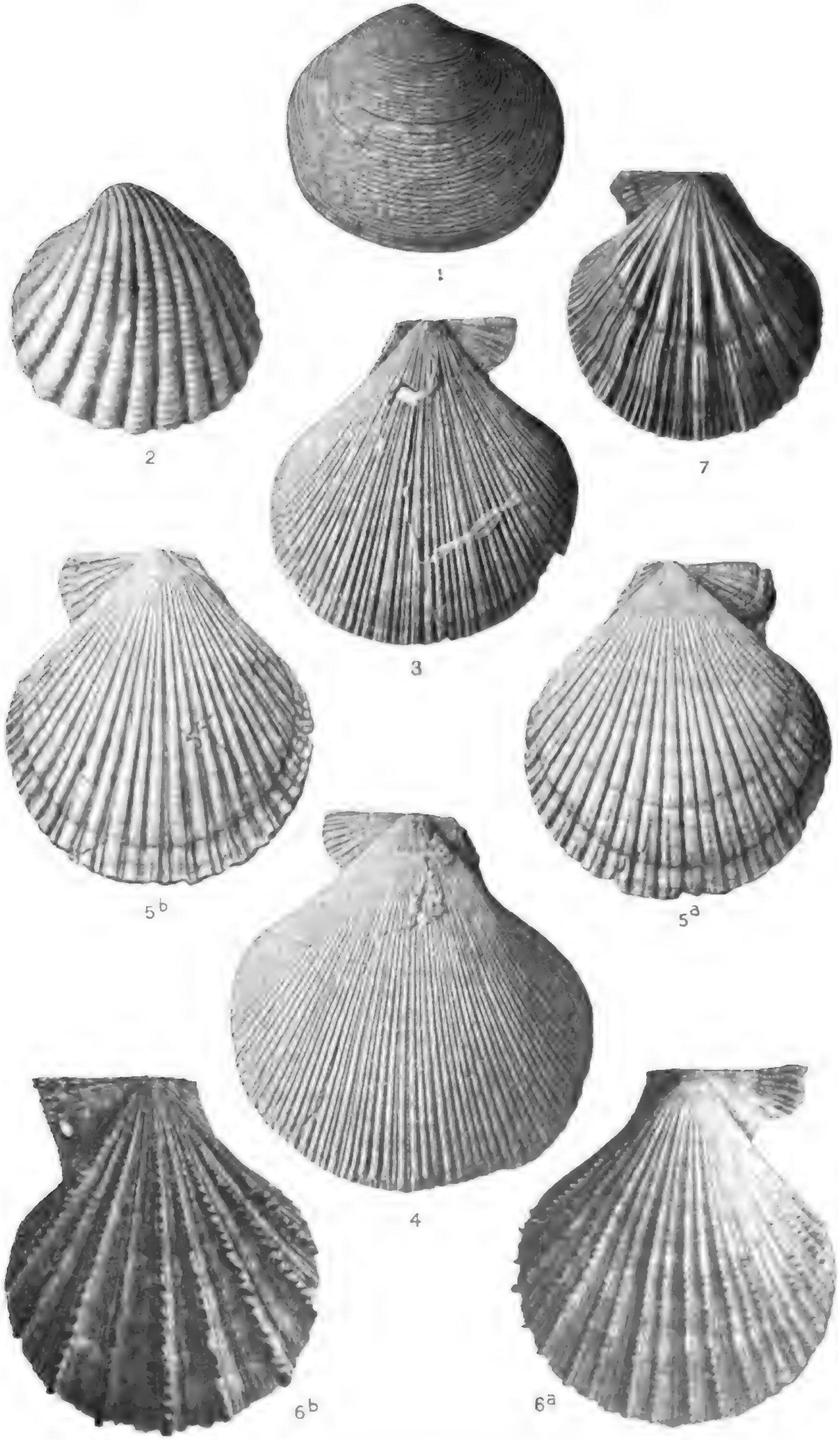
FIG. 5*a*. *Pecten* (*Chlamys*) *jordani* Arnold, U.S.N.M. 162522 (type). Exterior of right valve; altitude 45 mm. Pliocene, Deadman Island, near San Pedro, Cal.; also found in the Fernando formation at Santa Barbara and elsewhere.

FIG. 5*b*. Exterior of left valve of same specimen.

FIG. 6*a*. *Pecten* (*Chlamys*) *hastatus* Sowerby, collection of F. L. Button. Exterior of right valve; altitude 49 mm. Recent, Monterey, Cal.; found abundantly in the Fernando and equivalent formations throughout southern California.

FIG. 6*b*. Exterior of left valve of same specimen.

FIG. 7. *Pecten* (*Chlamys*) *hastatus* Sowerby, var. *strategus* Dall, collection of Delos Arnold. Exterior of left valve; altitude 36 mm. Fernando formation, Bath-house Beach, Santa Barbara. Characteristic of the Fernando formation.



FERNANDO (PLIOCENE) PELECYPODA.

PLATE XV.

Fernando (Pliocene) Pecten.

(Unless otherwise indicated, all figures are natural size.)

Fig. 1*a*. *Pecten* (*Pecten*) *bellus* Conrad, U.S.N.M. 165314. Right valve; altitude 92 mm.; view of exterior. Bath-house Beach, Santa Barbara. Characteristic of this region.

Fig. 1*b*. Left valve of same specimen. Altitude 85 mm.; view of exterior.

1b

1a

FERNANDO (PLIOCENE) PECTEN.

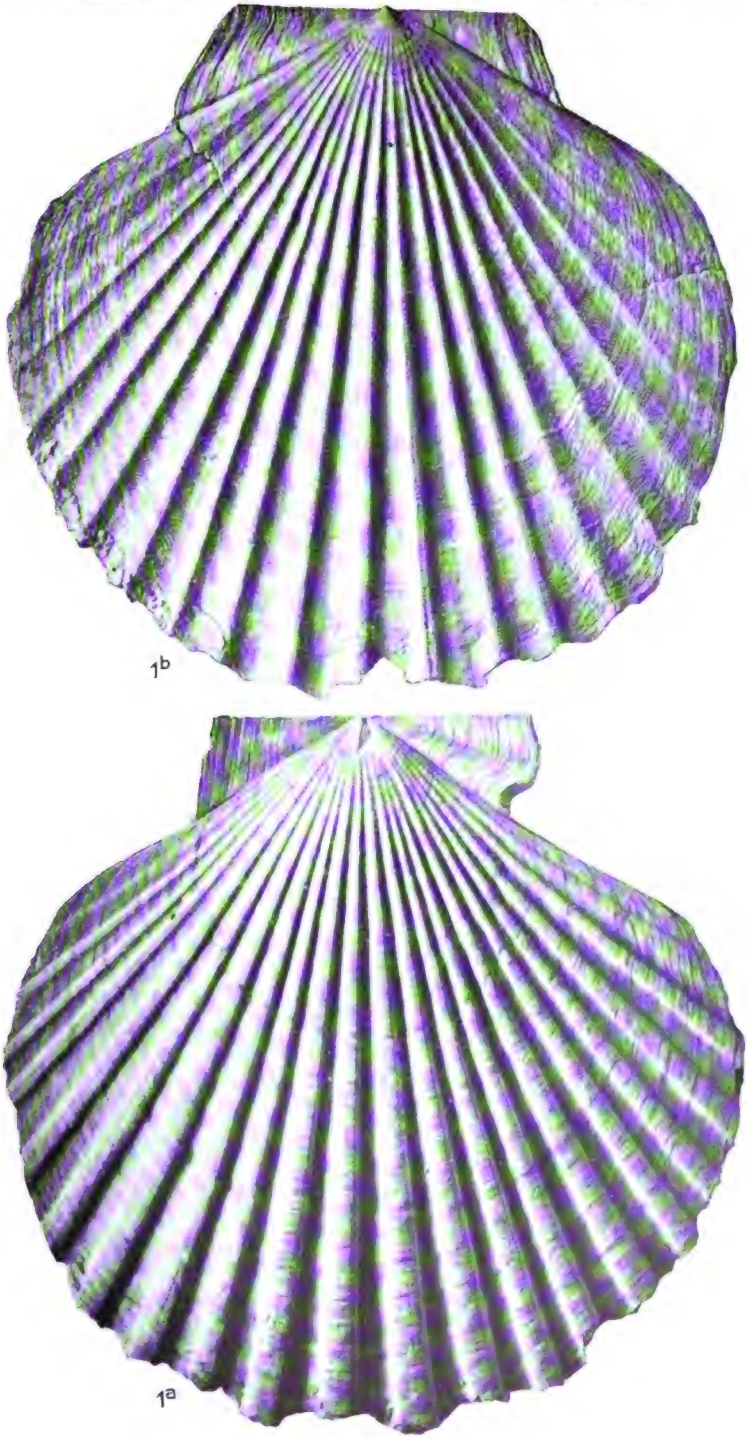
PLATE XVI.

Fernando (Pliocene) Pecten.

(Unless otherwise indicated, all figures are natural size.)

Fig. 1*a*. *Pecten* (*Patinopecten*) *caurinus* Gould, collection of Delos Arnold. Exterior of right valve; altitude 105 mm. Pliocene, Deadman Island, near San Pedro, Cal. Found in the upper part of the Fernando formation throughout the Coast Range.

Fig. 1*b*. View of left valve of same specimen.



FERNANDO (PLIOCENE) PECTEN.

PLATE XVII.

FERNANDO (PLIOCENE) BRYOZOA.

(Specimens figured are from Bath-house Beach, Santa Barbara.)

FIG. 1. *Crisia serrata* (Gabb and Horn) (*Crisina* id.). Front and side views of a portion of a segment, magnified. This minute bryozoan is extremely abundant in the fine washings. The lower end of each segment is pointed for articulation, while the distal extremity is blunt and receives the pointed end of the following segment.

FIG. 2. *Lichenopora californica* Gabb and Horn. Top, side, and basal views of an entire zoarium, magnified about four times.

FIG. 3. *Semitubigera tuba* Gabb and Horn. Views of zoaria, natural size; and front, side, and back views of a fragment, enlarged.

FIG. 4. *Idmonea californica* Conrad. Two fragments about natural size, and surface of one enlarged about eight times.

FIG. 5. *Idmonea californica* Conrad. Front and back views of two fragments, × 2. This is the most abundant bryozoan of the Santa Barbara deposits. Most of the incrusting species figured on this plate may be found attached to the smooth back of this *Idmonea*.

FIG. 6. *Entalophora? punctulata* Gabb and Horn. Gabb and Horn's figure of *Cellepora bellerophon*. This species is apparently founded on the basal expansion of *Entalophora punctulata*.

FIG 7. *Entalophora? punctulata* Gabb and Horn. A fragment of a zoarium slightly reduced in size, and an enlargement of the same.

FIG. 8. *Micropora disparilis* (Gabb and Horn) (*Reptescharinellina*). Magnified view of this incrusting species, which seems rather rare at Santa Barbara.

FIG. 9. *Membranipora californica* Gabb and Horn. Portion of a zoarium enlarged.

FIG. 10. *Membranipora barbarensis* Gabb and Horn. Several zooecia, × 15.

FIG. 11. *Membranipora multipora* (Gabb and Horn) (*Siphonella* id.). Surface, × 15. The zoarium of this species was described by Gabb and Horn as of free tubes, but the later collections contain many specimens showing it to be parasitic in growth.

FIG. 12. *Microporella californiensis* (Gabb and Horn) (*Cellepora* id.). Celluliferous side, × 15.

FIG. 13. *Schizoporella cornuta* (Gabb and Horn) (*Reptescharellina* id.). Celluliferous side of this incrusting species, × 15.

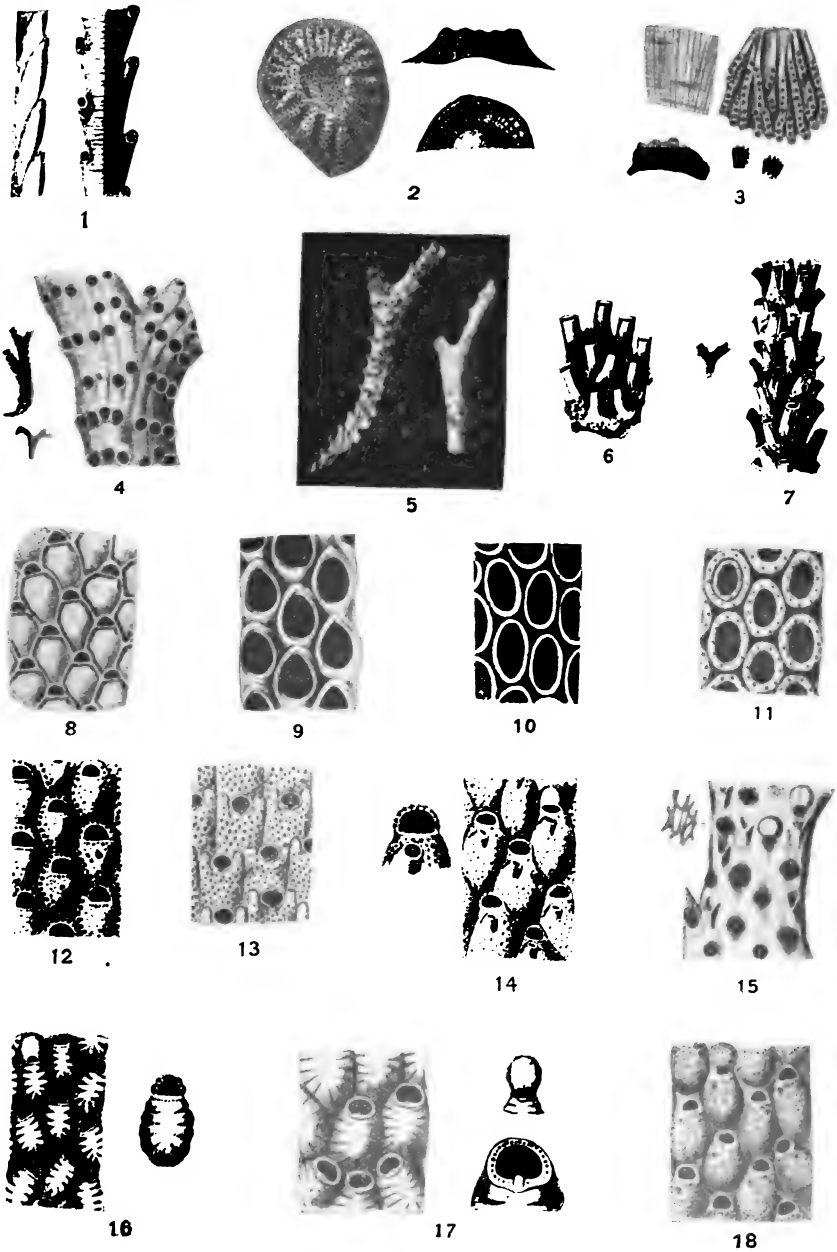
FIG. 14. *Lepralia eustomata* (Gabb and Horn) (*Reptoporina* id.). Portion of surface × 15, and zoarium still further enlarged. The conspicuous pore figured by Gabb and Horn proves on study of more specimens to be merely a broken avicularium.

FIG. 15. *Retepora labiata* (Gabb and Horn) (*Phidolopora* id.). A fragment of a zoarium, about natural size, and the surface of a branch, enlarged.

FIG. 16. *Cribrilina heermanni* (Gabb and Horn) (*Reptescharella* id.). Zooecia, × 15.

FIG. 17. *Cribrilina? plana* (Gabb and Horn) (*Reptescharella* id.). Second zooecia, × 15.

FIG. 18. *Lepralia heermanni* (Gabb and Horn) (*Reptescharellina* id.). Surface, enlarged. This species has not been detected in the recent collections, but it is believed to be based on a form of *Lepralia eustomata*. (See fig. 14.)



FERNANDO (PLIOCENE) BRYOZOA.

INDEX.

CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 321.]

The publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists can be had on application.

Most of the above publications can be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they can be obtained, free of charge (except classes 2, 7, and 8), on application.

2. A certain number are delivered to Senators and Representatives in Congress for distribution.

3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they can be had at prices slightly above cost.

4. Copies of all Government publications are furnished to the principal public libraries in the large cities throughout the United States, where they can be consulted by those interested.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports; Q, Fuels; R, Structural materials. This paper is the one hundred and second in series A and the one hundred and twenty-sixth in series B, the complete lists of which follow (PP=Professional Paper; B=Bulletin; WS=Water-Supply Paper):

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DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, DIRECTOR

GEOLOGY AND OIL RESOURCES

OF THE

SANTA MARIA OIL DISTRICT

SANTA BARBARA COUNTY
CALIFORNIA

BY

RALPH ARNOLD AND ROBERT ANDERSON

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GEOLOGY AND OIL RESOURCES OF THE SANTA MARIA OIL DISTRICT, SANTA BARBARA COUNTY, CAL.

By Ralph Arnold and Robert Anderson.

INTRODUCTION.

PURPOSE OF THIS REPORT.

During the last three years the region near the Pacific coast in the northern part of Santa Barbara County, Cal., has shown promise of becoming one of the most productive oil fields of the West, if not of the whole United States. The developed fields lie on the low, rolling hills between the Santa Maria and Lompoc valleys, where the oil has accumulated in great abundance in the Monterey shale, of middle Tertiary age, which underlies this region. The lightness of the oil, which averages from 25° to 27° Baumé, and the great productiveness of the wells, which yield as high as 3,000 barrels a day, with an average of 300 to 400 barrels, are among the features for which the district has become noted. Large areas in the same general region as the productive fields have been known for some time to be analogous, so far as surface evidence went, to the proved territory, and it was thought that geologic investigations of the region might furnish valuable information and aid in the extension of developments. Accordingly, with the purpose of studying the occurrence of the oil, the extent and structure of the oil-bearing formations, and their relations to associated formations, the writers carried on the field work leading to the present report during the summer and autumn of 1906. The geology of the region covered by the accompanying geologic map (Pl. I, in pocket) has not been completely studied in all parts. Between the San Rafael and Santa Ynez ranges it has been worked with considerable detail, but the mapping of the mountainous regions has been more in the nature of a reconnaissance outside of the areas of the Monterey formation.

A preliminary paper containing the features of this report most immediately pertinent to the oil developments and an outline map has been published as Bulletin No. 317 of the United States Geological Survey.

ACKNOWLEDGMENTS.

Mr. H. R. Johnson covered the territory northeast of the Santa Maria Valley, and the map and notes concerning that region are largely the result of his work. Dr. H. W. Fairbanks[a] is quoted on the geology of Point Sal.

The writers are greatly indebted to Mr. F. J. Keeley and Prof. C. S. Boyer, of Philadelphia, and to Dr. Albert Mann, of the United States Department of Agriculture, for information concerning diatoms and their relation to the origin of the oil. Acknowledgments are also due to Messrs. E. C. Sullivan, W. T. Schaller, and George Steiger for making analyses of the Monterey shale. The analyses of oil on pages 115-117 were made by H. N. Cooper and published by the California State Mining Bureau in its Bulletins Nos. 31 and 32. The indebtedness of the writers to Mr. Cooper and to the mining bureau for this information is hereby acknowledged.

Without the assistance of the operators in the developed field that part of the report which relates to the geology of the wells, production, and other technical data would have been an impossibility, and the writers therefore wish to acknowledge their indebtedness to the officers and managers of the different oil companies for their hearty cooperation and support. Thanks are due more particularly to Mr. W. W. Orcutt, geologist of the Union Oil Company; Messrs. J. F. Goodwin and F. J. Burns, of the Pinal and Brookshire oil companies; Judge John D. Bicknell and Mr. Morris Albee, president and secretary, respectively, of the Western Union Oil Company; Mr. Adolph Phillips, of the Graciosa Oil Company; Mr. W. O. Maxwell, of the Recruit Oil Company; Mr. Charles Off, of the Rice Ranch Oil Company; Mr. E. E. Henderson, of the Palmer Oil Company; Mr. F. D. Hall, of the Hall & Hall Oil Company; Mr. W. A. Irwin, of the Claremont Oil Company; Capt. N. P. Batchelder, of the Los Alamos Oil and Development Company; Mr. Frank M. Anderson, geologist of the Southern Pacific Company; Mr. William Vanderhurst, of the Todos Santos Oil Company; Mr. D. G. Scofield, vice-president of the Standard Oil Company, and many others whose assistance has added materially to the value of this report.

PREVIOUS KNOWLEDGE OF THE GEOLOGY.

Little attention has been given heretofore to the geology of the Santa Maria district. The earliest work was done by Thomas Antisell, with the assistance of observations by Albert H. Campbell, in the course of the explorations and surveys for the Pacific Railroad

[a] The geology of Point Sal: Bull. Dept. Geol., Univ. California, vol. 2, 1896, pp. 1-92.

in the early fifties.[a] In the report on this work the larger topographic features were well described, the presence of asphaltic rocks was briefly noted, and the Tertiary age of most of the sedimentary rocks was recognized, but the structural features and the relations of the rocks were in the main misinterpreted.

During the course of the geological survey of California by J. D. Whitney a hasty reconnaissance was made of a part of this region.[b] He says in his report:

> The region to the west of the San Rafael Range, between the Santa Ynez and Cuyamas rivers, was cursorily examined by our party. * * * The region is occupied by hills of moderate height. No metamorphic rock was seen; but pebbles of serpentine and metamorphic sandstone were noticed, especially for 3 or 4 miles north of Alamo Pintado. * * * These hills were covered with gravel derived from the bituminous slates. At times, especially near the Santa Maria River, the hills were capped by a modern horizontal deposit (post-Pliocene?). The underlying rock, when seen, was the bituminous slate, sometimes dipping to the north and sometimes to the south.
>
> Near Foxen's, on the south side of the valley, there were hills of nearly horizontal strata from 200 to 300 feet high, the north slopes of which were very steep, usually about 35°. Beneath the soft sandstone, which made up the principal part of these hills, was a stratum of infusorial rock resembling chalk in appearance, exceedingly light, its specific gravity not being more than 0.6 or 0.7; the thickness of this stratum was over 20 feet. The age of this formation is not yet definitely ascertained.
>
> North of the valley, at Foxen's, the bituminous slate occurs with a high dip to the north, and asphaltum is found in several localities near. In places the slates are altered and silicified, sometimes resembling semiopal in appearance, the finest laminæ of the original structure being preserved.

So far as the writers are aware no further investigation of the geology of the region was made until H. W. Fairbanks made examinations of portions of the Coast Ranges and reported on them for the State mining bureau in 1894. In his paper on the "Geology of northern Ventura, Santa Barbara, San Luis Obispo, Monterey, and San Benito counties" reference is made[c] to the region under discussion, especially to the Santa Ynez Mountains. Regarding the Santa Ynez Range he says: "It is formed, so far as is known, of Miocene rocks exclusively." And again:

> There can be no doubt that the main portion of the Santa Ynez Range is Miocene with a general anticlinal structure, well shown in the San Marcos Pass. The center of the anticlinal is not generally the highest portion of the range, but lies on the eastern slope. The normal type of anticlinal structure is also marked by an east and west compression, producing features, however, of secondary importance.
>
> As viewed from the south at various points the range consists of heavy-bedded sandstone, dipping at a high angle to the south. * * * At the western end, in the vicinity of Point Arguello, no anticlinal structure is apparent, but steeply inclined and broken strata. Asphaltum is found in many places near the sea from Point Arguello to Ventura County.

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[a] Pacific R. R. Repts., vol. 7, 1857, Chaps. VIII, IX, and X.
[b] Geological Survey of California, Geology, vol. 1, 1865, pp. 135–138.
[c] Twelfth Ann. Rept. California State Mining Bureau, 1894, pp. 498–506.

The present writers are in agreement with these statements except as regards the exclusively Miocene age of the rocks, a large part of which are here considered as Eocene. On page 505 of Fairbanks's article he speaks of "shales and sandstones of undoubted Cretaceous age" between Gaviota Pass and Santa Ynez River, in the hills which in the present paper are considered as part of the Santa Ynez Range. In the very short time spent in this locality the present writers found no evidence of the presence of Cretaceous rocks.

A number of asphalt deposits in northern Santa Barbara County are described on pages 30 to 33 of the twelfth annual report of the State mineralogist, cited above. The localities mentioned are on the Los Alamos grant, 4½ miles north of Harris station; along the northern slope of the hills bordering the Santa Maria Valley, 10 miles southeast of Santa Maria; about 2 miles northeast of the Purisima Mission; along the southern slope of the hills between the Los Alamos and Santa Ynez valleys (Purisima Hills), especially on the San Carlos de Jonata grant; and in poorer and less known deposits at Gaviota Landing, at Point Arguello, near the mouth of Canada Honda, and at other points toward Lompoc Landing. Seepages out of the bituminous "slate" (shale) series are mentioned as occurring in the canyon of the Sisquoc, about in the center of the Sisquoc grant, along Labrea Creek, and near the west end of the Tinaquaic grant.

By far the best observations recorded up to 1896 regarding the geology of this region were those of H. W. Fairbanks, published in his paper on the "Geology of Point Sal."[a] He gives a detailed description of the igneous and sedimentary formations occurring at the seaward end of the hills, termed in the present report the Casmalia Hills. In speaking of the even summit line of the Point Sal Ridge he says:

The regularity is due, in part at least, to the fact that the strata on the summit are nearly flat and composed of the resistant Miocene flints, while on the southern slope the bituminous shales are followed in descending order by a great thickness of gypsiferous clays, in which broad valleys have been eroded. Lower down toward the ocean the clays are replaced by strata of volcanic ash, sandstone, and conglomerate, in which, because of their greater resistance, canyons have been eroded. The strata of volcanic ash form very striking features in the landscape on the lower slopes of the ridge; being interbedded with soft clays they weather out in cliffs and projecting ridges.

In outlining the geology of the region of Point Sal Ridge, Fairbanks says:

The region about the point itself has been the scene of many violent disturbances and repeated eruptions of basic magmas. A part of these consolidated as surface flows, while others have the characters of deep-seated rocks.

The sedimentary strata comprise only the Pleistocene, Miocene, and Knoxville. * * * The Miocene is the most extensive formation represented. * * * It is

[a] Bull. Dept. Geology Univ. California, vol. 2, No. 1, 1896, pp. 1-92.

divisible into two distinct parts—the upper, the bituminous shales, and the lower, the gypsiferous clays. Below the clays are sandstone, shales, and conglomerates resting on the gabbro and serpentine. * * * The strata of volcanic ash appear in the lower Miocene beds. There are three distinct horizons, the lowest resting on the gabbro.

The igneous rocks are treated in especial detail in this paper and a very good description is given of the bituminous shales. The conclusions of the present writers are in agreement with the statements above quoted and the others contained in Fairbanks's paper.

In 1901 George H. Eldridge gave an admirable general outline of the topography and geology of the country surrounding the Santa Maria field in his treatise on "The asphalt and bituminous-rock deposits of the United States," and discussed in detail its asphalt deposits.[a] He says:

The geology of the region embraces an underlying series of folded Monterey shale of both the soft and more organic material and that which is hard and siliceous, but the former predominates. So far as observed by the writer this series of beds was not exposed at any point in its entirety. Overlying the Monterey unconformably, and especially developed in La Graciosa Hills, is the heavy and extensive deposit of Pliocene sands, grits, and conglomerate already referred to. The composition of the later deposit is chiefly quartzose.

Eldridge "observed a prevailing central fold somewhat to the north of the topographic axis of the ridge" south of Waldorf, in the Casmalia Hills, this being no doubt the fold described in the present report as the Schumann anticline. He says further:

The Pliocene * * * shows a less degree of folding than the underlying Monterey, yet the movement that produced the pre-Pliocene ridge has apparently been continued subsequent to the deposition of the materials of this age, for gentle dips of from 2° to 10° are to be observed in the later formation.

In discussing the country east of Los Alamos, between the San Rafael Range and the Santa Ynez Valley, which he calls the Los Alamos region, Eldridge says:

In structure the Los Alamos region presents a series of folds which are in general coincident with the topographic ridges and valleys. * * * It is worthy of note that the valleys of the region under consideration for the most part occupy the synclinal troughs. It is possible that some of them also occupy fault lines. * * * The general trend of the folds for the Los Alamos district, and indeed for a great stretch of country beyond, is N. 70° to 80° W., the dips being north and south. Excepting in their trend, however, there is but little regularity in the disposition of the folds, and their axes, both longitudinal and transverse, vary greatly in length. In addition to the main and conspicuous folding that has been described, there are frequent crumples of minor importance.

In another place Eldridge mentions a lens of limestone included in the serpentine in a high bluff just north of Alamo Pintado Creek, along the old beach line where the Fernando was deposited upon the Franciscan at the base of the San Rafael Mountains. This lime-

[a] Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 1, 1901, pp. 424-441.

stone was composed largely of Pliocene shells, as determined by Doctor Dall. Eldridge remarks: "In view of the supposed age of the serpentine, it is thought that the deposit was formed by the accumulation of sediment and shells in a crevice of the older rocks at the time they perhaps formed the sea bluffs."

The same writer published a brief summary of his knowledge concerning the Santa Maria district in 1903.[a]

The San Luis folio,[b] by H. W. Fairbanks, issued in 1904, contains much that relates to the district in general, although it pertains directly only to the part containing the Arroyo Grande field. It is the most comprehensive report concerning the northwestern part of the Santa Maria district yet published.

The present writers have published two papers concerning the geology and economic resources of the Santa Maria district. The first is entitled "Diatomaceous deposits of northern Santa Barbara County, Cal.,"[c] and the second "Preliminary report on the Santa Maria oil district, Santa Barbara County, Cal."[d] A third paper treating more in detail the burning of the shale is "Metamorphism by combustion of the hydrocarbons in the oil-bearing shale of California," to be published in the Journal of Geology.

EARLY HISTORY OF THE DISTRICT.

The Santa Maria district was up to 1899 entirely unknown as an oil-producing territory. To Messrs. McKay and Mulholland, of Los Angeles, is due the credit for starting operations in the Santa Maria field proper. After a favorable report had been made by Mr. Mulholland on certain lands of the Careaga ranch, the Western Union Oil Company was organized, drilled three prospect holes, and was finally rewarded in August, 1901, by striking paying quantities of oil in the third well. In 1902 the Pinal Oil Company, of Santa Maria, began operations on the north side of Graciosa Ridge, and meeting with marked success was followed by the many other companies that have since undertaken operations in this field.

Successful wells were drilled in the Lompoc field in 1904, and since that time the further development of this part of the district has been assured. A later field to attract attention is that adjacent to the town of Arroyo Grande, where development is well under way, being stimulated by the completion of the successful Tiber well No. 1 late in 1905. Prospecting is now (January, 1907) going forward in the Huasna field east of the Arroyo Grande field, and the operators there confidently expect to develop productive wells.

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[a] Contributions to economic geology, 1902: Bull. U. S. Geol. Survey No. 213, 1903, p. 313.

[b] Geologic Atlas U. S., folio 101, U. S. Geol. Survey 1904.

[c] Bull. U. S. Geol Survey No. 315, 1907, pp. 438-447.

[d] Bull. U. S. Geol. Survey No. 317, 1907, pp. 1-69, 2 pls., 1 fig.

GEOGRAPHY AND TOPOGRAPHY.

LOCATION.

The region discussed in this paper is situated on the California coast in Santa Barbara County, between 120° and 120° 40′ west longitude and 34° 30′ and 35° north latitude. In areal extent it is about 1,300 square miles and it practically covers the Lompoc and Guadalupe quadrangles as topographically mapped by the United States Geological Survey. It includes portions of the San Rafael and Santa Ynez divisions of the Coast Ranges and the basin region lying between them, which is occupied by the Santa Maria, Los Alamos, and Santa Ynez valleys and the intervening hill ranges. It is bordered on the north by the San Luis Obispo County line, on the west and south by the Pacific Ocean, and on the east by the Santa Ynez quadrangle, which covers the high, wild mountains north of Santa Barbara. On its west coast are Point Sal and Point Arguello, and the south coast includes Point Conception and part of the long, straight shore line that runs due east from that point toward Santa Barbara. These are among the most prominent coastal features of California.

The region is thoroughly intersected by roads, except in some of the uninhabited portions. The Southern Pacific Railroad coast line, part of the transcontinental system, extends close to the ocean entirely around two sides of the area, and the Pacific Coast Railroad, a local line from Port Harford and San Luis Obispo, runs into the region as far as Los Olivos via Santa Maria. A rough estimate would place the number of inhabitants of this region between 5,000 and 10,000.

The Arroyo Grande and Huasna oil fields, in the San Luis quadrangle, San Luis Obispo County, are also briefly mentioned, although not a part of the region whose general features are described in this report.

DEFINITIONS OF PLACE NAMES.

The following list defines certain place names as used on the map and in this report. The two main mountain ranges have heretofore been indefinitely designated The other names are newly applied.

The only land comprised within the Guadalupe quadrangle is the narrow strip of coast west of longitude 120° 30′ W. The Lompoc quadrangle covers the rest of the area shown on the map east of that line.

The San Rafael Mountains include the whole group between Santa Ynez and Cuyama rivers.

The Santa Ynez Mountains include the whole range east of Point Arguello between Santa Ynez River and the ocean.

The Casmalia Hills include the group extending from the coast at Point Sal to Graciosa and Harris canyons and San Antonio Valley.

The Solomon Hills lie between the Santa Maria Valley, Foxen Canyon, and the Los Alamos Valley, and between Divide and La Zaca Creek.

The Purisima Hills lie between Lompoc, the Santa Rita Valley, and the Santa Ynez Valley on the south and the Los Alamos Valley on the north, and between Burton Mesa on the west and Alamo Pintado Creek on the east.

The Santa Rita Hills lie between the Santa Ynez and Santa Rita valleys, extending from a point east of Lompoc nearly to the east edge of the Santa Rosa grant.

The name San Antonio terrace is applied to the wide terraced region between Casmalia and the west end of the Los Alamos Valley.

The Lompoc terrace is the plateau-like region of hills extending from the coast a distance of about 5 miles east from Honda and the same distance southeast from Surf.

In 1896 H. W. Fairbanks used the names "Point Sal Ridge" for the axis of the hills between Mount Lospe and Point Sal, and "Lions Head" for a high, rugged mass of serpentine on the coast south of Point Sal. These features are so named here.

RELIEF.

GENERAL STATEMENT.

The general character of the region covered by the Lompoc and Guadalupe quadrangles is that of a triangular hilly basin opening out toward the coast between two divergent ranges of mountains—the San Rafael Range in the northeast portion of the area and the Santa Ynez Range bordering it on the south. At the east edge of the area mapped these ranges are divided only by the valley of Santa Ynez River and the foothills north of it. Farther west the distance between them grows to 30 miles or more. The region situated in this angle is primarily a basin, owing its character and the details of its structure to its position between these ranges. This basin region, its structure, and its oil deposits form the principal subjects of discussion in the present paper.

Two lines of hills and three valleys occupy this trough between the two main ranges, radiating like the intermediate ribs of a fan between the lines that bound them. The more northerly of the two lines of hills is that of the Solomon and Casmalia hills, which are separated from the San Rafael Mountains by the wide valley of Santa Maria River. The more southerly is the range of the Purisima Hills, which is separated from the Santa Ynez Mountains by Santa Ynez River. These two lines of hills are themselves divided by Los Alamos Valley.

They are topographically and structurally young ranges, except the Casmalia Hills, at the extremity of the northern line, which have the character of a separate and old range.

SAN RAFAEL MOUNTAINS.

The most prominent topographic feature is the great mass of the San Rafael Mountains on the northeast and east, 25 to 30 miles back from the ocean. The structural trend of the range is N. 50° W., approximately parallel with the general course of the lines of structure in California, although on the whole more westerly. The range runs obliquely to the north-south coast line west of it, but farther north, where the Santa Lucia Range, its northward continuation, approaches the ocean the coast curves to the northwest under the control of the mountains.

Although the portion of the San Rafael Range included within the area shown on Pl. I (pocket) composes a high, rugged maze of ridges reaching elevations that range between 2,000 and 4,300 feet, this portion is in the larger aspect, but subsidary to the main mountain group farther east, in which altitudes approaching 9,000 feet are attained. The ridges are divided by steep canyons, most of which cut transversely across the formations regardless of the folding and structural lines. Rounded soil-covered slopes form a considerable portion of the part of this range included in the Lompoc quadrangle, but rough, rocky slopes are likewise abundant. The range is traversed centrally by the well-graded canyon of Sisquoc River, which divides it into two mountain groups. On the south and north the range is bounded by wider graded valleys—those of Santa Ynez and Cuyama rivers. The Santa Ynez divides two distinct ranges. The Cuyama forms a more arbitrary division in the Coast Ranges. Near its mouth, at the point where it reaches the area included in the accompanying map, it veers to the south and cuts a narrow gorge across the San Rafael Mountains without regard to the structure. The range may be regarded as continuous across this portion of the river.

Within the triangular area mapped the high ridges and mountains around Zaca Lake, Bone Mountain, Tepusquet Peak, and Los Coches Mountain are boldly defined, with steep side slopes descending into narrow canyons, and as a rule rounded summits. The broad ridge originating north of Los Coches Mountain and extending southeastward to North Fork of Labrea Creek, where its character is temporarily lost until it appears again in Manzanita Mountain, is a striking feature with its long southwestern and abrupt northeastern slopes. The seaward flanks of the range terminate rather abruptly in the terraces bordering the Santa Maria Valley.

SANTA YNEZ MOUNTAINS.

The Santa Ynez Mountains form a long, narrow range bordering the Santa Barbara Channel and bounded on the north by the westward flowing Santa Ynez River. The trend of the range is east and west and has determined the unusual direction taken by the coast south of it. The range is about 9 miles in average width and contains two lengthwise zones. The southern zone comprises a ridge with remarkably even sky line, which rises directly from the sea. This ridge increases in height toward the east from an elevation of 1,000 feet at Point Conception to 3,800 feet east of Refugio Pass and more beyond the boundary of the area mapped. At Point Conception the coast bends abruptly to the northwest around the end of this ridge, but north of Jalama Creek a similar ridge, that of the mountain El Tranquillon, follows the coast as far as Point Arguello, where the shore bends again abruptly and assumes a northward course. The second zone lies between these two coast ridges and Santa Ynez River. It has more the nature of a foothill region, forming a partly individual range of hills and ridges separated from the coastal ridge by longitudinal valleys. The average slope from the summit of the range down to the sea is at an angle of 20° to 30°. In places the angle is less, but on some individual slopes it is greater. The width of the range on the north of the summit ridge is greater and the slope more gentle and more broken than on the southern abrupt slope to the sea. Viewed from the ocean on the south the range has the appearance of a steep, even-topped breastwork; from the north it appears as a belt of discontinuous hills and ridges grouped in front of and almost hiding the long culminating ridge. The Santa Ynez Range forms the most prominent elbow on the California coast.

The topography of this range reflects the structure more than does that of the San Rafael Mountains, and deformation within it does not appear to have gone so far.

In the high mountainous region east of the area mapped, north of Santa Barbara and south of the south end of the great central valley of California, centering at Mount Pinos, lies the point of convergence of all the ranges of mountains in this part of California—the Santa Ynez Range coming in from the west; the San Rafael Range from the northwest; the Santa Lucia and San Jose ranges from the country north of Cuyama River; the Mount Diablo Range, or easternmost member of the Coast Ranges, from still farther north of west; the Tehachapi Range, running southwestward from the south end of the Sierra Nevada; and the San Gabriel Range, which comes from the southeast as the continuation of the Coast Ranges in southern California. Here the northwest-southeast lines of structure, dominant throughout the major part of the State, are met

and opposed by the east-west structure of the Santa Ynez Range, and the result is this convergence of ranges with the consequent formation of a high, structurally complex region. The Lompoc quadrangle is on the western outskirts of this region, and the lines of relief corresponding to the two lines of structure are here beginning to diverge and show their individuality in the two bounding ranges.

SANTA MARIA VALLEY.

Santa Maria River, which takes its rise in two profound valleys within the San Rafael Range, flows along the foot of this range at the north edge of the Santa Maria Valley. This valley is a wide flood plain with an even cultivated floor, surrounded by low terraces that fringe the base of the mountains on the northeast and rise into the Solomon Hills on the south. It opens out to the sea and forms the southern part of the low region lying between Pismo Beach in San Luis Obispo County and the Casmalia Hills.

CASMALIA HILLS.

The most prominent feature of the landscape south of the Santa Maria Valley is a long ridge with a level sky line running northwestward out to the ocean at Point Sal. This is the high ridge of the Casmalia Hills, which rises abruptly from the Santa Maria Valley. Its highest point is Mount Lospe, 1,624 feet above the sea. The slope up to this ridge from the valley on the northeast is steep, but on the north the rise is more gradual over wide slopes of dune sand. On the southeast the ridge declines as it approaches Schumann Pass, the low divide over which the railroad crosses from the Santa Maria Valley to Schumann Canyon; on the south it forks into successive ridges which slope gradually into terraced hilltops bordering Schumann Canyon; on the west it drops off abruptly into steep, rocky declivities that fringe the sea in the neighborhood of Point Sal. The ridges continue southeastward opposite Schumann Pass as far as Graciosa Canyon, where they sink under more recent sand formations and lose their character. South of Schumann Canyon the terraced slope continues in the San Antonio terrace as a wide plateau locally intersected by sharply defined U-shaped canyons. The Casmalia Hills, particularly that portion north of Schumann Canyon, have a distinct individuality among the topographic features of the basin region, and may be regarded as a separate although small range allied in age and character with the bounding ranges. It is conformable in trend with the San Rafael Mountains and forms a prominent headland jutting out to sea.

Most of the ridges in these hills follow the strike of the beds. Their summits are characteristically of gentle incline; the side slopes

range from gentle to fairly steep, being in many places determined by the dip. Pl. IX, *A* (p. 80) shows excellent examples of the strike ridges, dip slopes, and even sky lines of these hills. The ridges diverging from Mount Lospe are given prominence by the hard flint of which they are formed, and the sharp outlines of the slopes along the coast southward from Point Sal are caused by the resistant igneous rocks there exposed.

South of the Casmalia Hills the sea has cut into soft formations and along structural lines, so as to leave the Point Sal Ridge jutting out as a promontory. The same is true on a smaller scale south of Purisima Point, the seaward extension of Burton Mesa, and south of the west end of the Santa Ynez Range. The coast north of each of these headlands runs northward, with only a gentle curve away from the point, until the indentation south of the next range is reached. The east-west coast lines follow structural features; the north-south lines truncate them. Faults are not concerned in any of the north-south features along this part of the coast.

North of the Casmalia Hills the coast forms a straight north-south line bordering the lowland that opens out at the mouth of the Santa Maria Valley as far as the deep indentation at the base of the San Luis Range, which exhibits the best example of this type of coastal structure. The latter range lies in the San Luis quadrangle and has been described in the folio covering that region.[a]

SOLOMON HILLS.

Although the Casmalia Hills drop into insignificance in the vicinity of Graciosa and Harris canyons, their general line of topographic relief continues with a more easterly course toward the San Rafael Mountains, the whole being in fact a spur of this range. The Solomon Hills are a group of low, rolling hills covering a wide area between the Santa Maria and Los Alamos valleys. From a distance the area looks like an undulating plateau sloping away on all sides except the east to wide, slightly inclined or flat valleys.

The features of the topography of the Solomon Hills are shown in Pl. XI (p. 98). From a point near at hand the individual hills and valleys of irregular round and square forms assume bold outlines. The angular slope of hills capped with low-dipping beds of sand and having steep, squarish flanks is very characteristic of the region. Many ridges have fairly flat summits, which slope gently, with a long, even sky line, and are due to surface cappings of sand hardened by iron oxide. Such a capping has in places the appearance of a resistant bed forming the ridge top and determining the slope by its low dip.

Mount Solomon has an elevation of 1,338 feet and other peaks rise

[a] Geologic Atlas U. S., folio 101, U. S. Geol. Survey, 1904.

as high as 1,600 feet. A common height for summits in these hills is 1,200 feet.

Wide, shallow, filled valleys between the rolling summits are characteristic of the Solomon Hills, the soft valley filling being as a rule sharply cut along a meandering course by a miniature stream gorge that has been rapidly eroded. Many of these recent channels are deeper than they are wide. In the vicinity of La Zaca Creek on the east the Solomon Hills merge with these foothills, and the general topographic features are continued in them. The Solomon Hills owe their low outlines largely to their structural development rather than to their topographic maturity. It has been an area of building up as well as of wearing away, and the original topography, which reflected characteristically the folds of the sedimentary formations, has been obscured by further deposition and by the filling of valleys, in addition to alteration by erosion.

LOS ALAMOS VALLEY.

The incline of the Solomon Hills on the south is gradual down to the Los Alamos Valley. This valley extends from the region where the Solomon and Purisima hills coalesce in the foothills of the San Rafael Range a distance of about 27 miles to the coast, in a direction about N. 75° W. This, it will be noted, is much more westerly than the trend of the Santa Maria Valley. The Los Alamos Valley separates the two basin ranges—the Solomon and Purisima hills—and is a drainage feature of them alone. The average altitude at the summit of its watershed is from 1,000 to 1,300 feet; and the highest elevation that the watershed reaches anywhere is less than 2,000 feet. All the water from the higher surrounding regions that drains into the Santa Maria basin region escapes either into the Santa Maria Valley on the north or the Santa Ynez Valley on the south.

PURISIMA HILLS.

The second of the two hill ranges is that of the Purisima Hills, which forms a definitely outlined structural and topographic unit springing from the plateau region about Santa Ynez and the foothills of the San Rafael Range in the vertex of the triangular basin. It rises at that point in the shape of a number of strike ridges which run northwestward and then curve around to the west, coming together. For most of the distance to the ocean beyond this junction the range consists of a single ridge running parallel to the Los Alamos Valley. On the north it sends out lateral ridges that drop off rather abruptly into the Los Alamos Valley. These ridges are separated by fairly sharp V-shaped valleys, although some of the valleys have sides of more gentle slope and filled bottoms. A striking topographic feature is a

longitudinal trough running for miles parallel with this range and the Los Alamos Valley and cutting across the ends of the above-mentioned ridges at right angles to them, at a distance of one-half to 1 mile from the valley. It notches all the ridges and leaves an individual row of knobs 100 to 200 feet in relief bordering the valley. This depression is not a continuous drainage feature, but is stratigraphically of importance as approximately marking the contact between the Monterey shale and the loose Fernando sand. On the south side of the summit of the Purisima Hills the lateral ridges extend a long way with a uniform gentle slope, like remnants of an eroded inclined plateau. At their base, some miles from the summit, and usually from 500 to 1,000 feet below, these southern slopes merge into an undulating hilly plateau that has the appearance of being buried under soft recent sand. The range is broadest at the east end, where it consists of a number of parallel ridges. The point of convergence of some of these is Redrock Mountain, which is 1,968 feet high and the highest summit in these hills. Thence westward the hilly zone narrows into a single central ridge and its offshoots, and gradually pinches out, finally giving place on the south and west to a broad terrace in which its hilly character is lost. The summit of the main ridge of the Purisima Hills west of Redrock Mountain gradually declines in height and for most of the way it is remarkably even, the elevation varying between 1,200 and 1,000 feet. At the elevation of 1,000 feet it grades into the smooth terrace called Burton Mesa.

BURTON MESA.

Burton Mesa is a marine terrace covering more than 50 square miles, which slopes, with an average gradient of 2½ per cent, away from the west end of the Purisima Hills, reaching the sea within 7½ miles. It is composed of Monterey shale, in the main rather gently folded, which has been planed off and covered with a thickness of about 25 feet of horizontal gravel and loose sand. From the elevation of 1,000 feet, where the continuous sheet of sand overlaps on the end of the Purisima ridge, down to the 600-foot level the distance in a west-southwest direction is three-fourths of a mile and the slope 10 per cent. Within the next three-fourths of a mile a drop of 100 feet occurs, the slope being 2½ per cent. Beyond lies the main level stretch of the plateau for a distance of 5 miles, with no greater slope than three-fourths of 1 per cent until the elevation of 300 feet is reached, in the southwest corner of the mesa, where there is an abrupt change to a 10 per cent slope, the distance down to elevation 100 feet being only one-third of a mile. Below the 100-foot level there is a bench with a 3 per cent grade as far as the edge of the cliff which faces the sea, and which is in most places about 25 feet above the water. North

of Canada Tortuga the steeper portion above the coastal bench is only 100 feet high, and in the northwest corner of the mesa the main terrace and the coastal bench grade into each other and become practically one.

SANTA YNEZ VALLEY AND SANTA RITA HILLS.

Santa Ynez River is the second of the two main drainage lines of the area, Los Alamos Creek, the next in size, being much subordinate to these two. The Santa Ynez rises in the high region north of Santa Barbara and flows westward between the Santa Ynez and San Rafael ranges. From the east edge of the Lompoc quadrangle, where these two ranges diverge, it flows slightly to the north of west, at the foot of the Santa Ynez Mountains. Its course is even more westerly than that of the Los Alamos Valley until it approaches the ocean, where the nose of the Santa Ynez Range, as in the two ranges farther north, shows a tendency to change its orientation into greater conformity with the northwesterly course of the San Rafael Range.

This stream has a low gradient of only one-fourth of 1 per cent. Its valley has a steep side on the south formed by the hills of the Santa Ynez Range, but it is widened on the north by the easy slopes of terraces and sand hills, except at the Santa Rita Hills, which rise midway in the river's course.

The Santa Rita Hills form a small separate range reaching a height of 1,300 feet and resembling in miniature the Purisima Hills. The range starts from the valley in several strike ridges running northwest, which join in the highest part of the range and then continue due west as a single ridge. The river follows a tortuous course between this and the Santa Ynez Range and has cut cliffs in many places. On the north the Santa Rita Hills are divided from the Purisima Hills by the Santa Rita Valley, a low basin similar to some portions of the Santa Ynez Valley.

The level floor of the river valley, including the stream bed and the somewhat higher terrace-like flats on either side, ranges in width from a few hundred feet to about a mile until within 10 miles of the ocean, where it opens out into the Lompoc Valley, an alluvial flat several miles wide.

TERRACED COAST.

Pleistocene terraces border the coast for the greater part of the distance around the Guadalupe and Lompoc quadrangles. The great Burton Mesa terrace has already been mentioned. Beyond the valleys to the north and south of this mesa similar terraced areas extend widely and in places to a considerable distance inland, but nowhere else with so gentle a slope as is exhibited on the Burton Mesa.

Where steep hills descend toward the coast there is almost without exception a coastal terrace starting at the top of the sea cliff, which, as a rule, ranges in height from a few feet to more than 50 feet above the water. Most of these terraces extend up to an elevation greater than 200 feet. Some of them have left traces at a height of 300 feet or more, and others continue perfect to this altitude or even higher.

GENERAL TOPOGRAPHIC FEATURES.

The point of especial interest in the topography of the central region between the two bounding ranges is its characteristic reflection of the structure of the formations, whereas in the mountains, as has been noted, the topographic development has been less in accordance with the lines of structure. An anticline in the central region is apt to be coincident with a ridge, as, for example, in the long ridge of the Purisima Hills, which lies close to the axis of a broad anticline. Moreover, some of the larger valleys mark the synclinal axes of the broad lines of structure—a statement illustrated by the Santa Ynez Valley in parts and by its structural, although not actual, continuation in the Santa Rita Valley. It is also exemplified by the upper portion of the Los Alamos Valley and by Harris Canyon. These topographic features may be accounted for by the facts that the main movements in these hill ranges have been gentle as compared with those in the older mountain masses, that the disturbances giving them form have been comparatively recent, and that deformation has not gone so very far. Wherever there are low areas of rolling hills it is almost sure to be found that a syncline or plunging fold has given rise to structural depressions in which deposits of soft sand producing low topographic forms have been laid down.

The character of the different formations shows its influence on the topography. The areas of serpentine with associated Franciscan rocks have irregular broken surfaces with many outcrops and usually an old, well-worn appearance. The dominantly sandstone and shale terranes described under the headings "pre-Monterey rocks" and "Vaqueros, Sespe, and Tejon formations, undifferentiated," do not give rise to a very distinctive topography. They form a succession of ridges and V-shaped canyons of moderate relief and comparative regularity. In many places the truncated edges of the tilted strata form steep, rough strike slopes. The Monterey shale produces the forms of highest relief in this region, as well as forms of low relief, according to the amount of folding that has taken place in it and to its hardness. The brittle shale closely folded gives rise to sharp ridges, many of them serrate, with steep, rocky flanks. Ridges of highly tilted shale are shown in Pl. VI, *B* (p. 46). The lower folds produce hills of gentle incline and long unbroken ridges, in places parallel with the strike

and having a dip slope, as shown in Pl. IX, *A* (p. 80). Characteristic of the soft shale are hills having the form of mounds with symmetrical rounded contours and with few prominent outcrops except pavements of shale forming the surface. The soft Fernando sands form small hills that look like irregular sand piles, and long slopes with shallow erosion features. Some of these slopes reflect the dip of the strata on the flanks of low folds and are structurally inclined plateaus in a typical state of youthful dissection. The valleys are, in many places, filled with sand that has shifted down from the hills faster than it could be carried away by agencies of transportation. Great cliffs of soft sand are common as the result of the rapid undermining and removal of portions of hills. Thus walled cirques are formed. Harder materials in the Fernando cause squarish forms, such as that of Mount Solomon. The terraces of the Quaternary give a strong individuality to the topography of this region. They are widely in evidence along the coast, in valleys, at all levels up to 1,200 or 1,400 feet on slopes, on hilltops, and along horizon lines.

DRAINAGE AND RAINFALL.

The three principal streams have received mention under the previous headings. A small amount of water runs in them all the year round, but the quantity is only rarely sufficient in either of the two main streams to warrant their being called rivers. This name is applied to them on the ground of the importance of their drainage areas. Almost all the drainage of the two quadrangles flows into these three streams. In the main they run parallel to the strike of the formations. In addition to those already mentioned, others that run independently into the sea are Casmalia Creek, in Schumann Canyon, which first cuts obliquely across the end of the Casmalia Hills and then assumes a longitudinal course; Canada Honda Creek and Jalama Creek, the two last having deeply cut courses parallel with the structural lines at the west end of the Santa Ynez Mountains. The steep seaward slope of these mountains is cut into by a great number of short, steep, transverse gorges.

The portion of the San Rafael Range lying within the area covered by the map is drained principally by Sisquoc and Cuyama rivers, which flow along well-graded courses, and by the minor streams, Labrea and Tepusquet creeks. With the exception of the Cuyama, these watercourses and the majority of the others in the mountains have cut transverse canyons across the formations regardless of the folding and the structural lines. In this respect they differ from the streams farther south.

On the whole, it is rather a dry region. An average of only 12 or 15 inches of rain falls annually, during the winter rainy season. During

the long dry season almost complete evaporation of surface moisture takes place, and there is little erosion through the aid of water. Throughout the latter part of the Quaternary period the rate of erosion has probably been slow.

CLIMATE AND VEGETATION.

The climate of this area is that of the coastal region of California. It is equable the whole year round, excessive heat or cold being very rare. The days are mild, the nights chilly. The region is subject to the inroads of heavy fogs and driving winds from the open ocean, but this is true to a lesser degree in the eastern angle of the basin, where there are protecting hills on all sides. The winds blow very strongly from the west and northwest up the radiating valleys that open to the coast. The region is subject to earthquakes, some of which would seem to be of local origin.

The vegetation in the northern part of Santa Barbara County is open, as in the neighboring portions of California. There are almost no dense groves of trees, most of the hills being sparsely clothed with a scattering growth of small trees, usually live and white oaks, and bushes, or else entirely bare, except for sagebrush and grass. The wide terraces and hills of soft sand are commonly overgrown with so-called tarweed and are otherwise almost bare. In the valleys near the coast grow many willows; in the more protected valleys farther inland thrive large sycamores, cottonwoods, and live and white oaks. The steep slopes of the San Rafael Range are sparsely set with small oaks, pines, and yuccas, and, like those of the Santa Ynez Range, are covered in parts by dense thickets of undergrowth.

The vegetation of the hill ranges of the basin region is typically illustrated by Pl. IX (p. 80) and of the San Rafael Mountain region by Pl. VI (p. 46).

GEOLOGY.

SEDIMENTARY FORMATIONS.

GENERAL STATEMENT.

The formations involved in the geology of this district (see Pl. II) include the Franciscan (Jurassic?); Knoxville (lower Cretaceous); pre-Monterey rocks (which may include both Cretaceous and older Tertiary); Tejon, Sespe, and Vaqueros, undifferentiated (Eocene-Miocene); Monterey (middle Miocene); Fernando (Miocene-Pliocene-Pleistocene); and Quaternary. The maximum known thickness of the Tertiary and early Quaternary formations combined is 13,200 feet. The following table shows the correlation of these formations with the

standard California section and with that of Santa Clara Valley, Ventura County:

Tentative correlation of formations of Santa Maria district with the standard California Coast Range section and with that of the Santa Clara Valley.

Era.	System.	Period.	Standard Coast Range section.	Santa Maria district section.	Santa Clara Valley section.
Cenozoic.	Quaternary.	Recent.	Alluvium.	Alluvium.	Alluvium.
		Pleistocene.	San Pedro. Unconformity	Terrace deposits and dune sand. Unconformity	Sand and gravel. Unconformity
	Tertiary.	Pliocene.	Merced.		
			Purisima.	Fernando.	Fernando.
		Miocene.	San Pablo. Unconformity	Unconformity	Unconformity
			Monterey.	Monterey.	Modelo: Shale. Upper sandstone. Shale. Lower sandstone.
			Vaqueros.	Vaqueros, Sespe, and Tejon, undifferentiated (including some Monterey in Santa Ynez Range).	Vaqueros.
		Oligocene.	San Lorenzo. Unconformity?		Sespe: Upper. Red beds. Lower.
		Eocene.	Tejon.		Topatopa.
			Martinez. Unconformity?		
Mesozoic.	Cretaceous.		Chico. Unconformity	(?)	(?)
			Horsetown. Unconformity		
			Knoxville. Unconformity	Knoxville.	
	Jurassic (?).		Franciscan. Unconformity	Franciscan.	Unconformity
			Granite, schist, etc.		Granite, gneiss, etc.

FRANCISCAN FORMATION (JURASSIC?).

The oldest rocks within the Santa Maria district belong to the Franciscan formation, which is probably of Jurassic age. H. W. Fairbanks described the same formation under the name San Luis in the San Luis folio. The Franciscan is a very important basement formation in the Coast Ranges farther north. The small areas of these rocks occurring here consist of remnants of beds of sandstone, shale, glaucophane schist, and jasper associated with serpentine that has probably been intrusive in them. The sandstone is usually of a dark-green color, fairly fine grained, and considerably indurated. The jasper is banded by thin contorted beds. These sediments are so

disturbed that little clew as to their structure can be obtained, and so local in extent that no attempt has been made in mapping to differentiate them from the accompanying serpentine.

KNOXVILLE FORMATION (LOWER CRETACEOUS).

Several small areas of sedimentary rock occur which can be definitely assigned on fossil evidence to the Knoxville, or lower Cretaceous. The two most important are north of Mount Lospe, in the Casmalia Hills. The rock is chiefly dark-colored, unaltered argillaceous shale, such as is characteristic of the Knoxville throughout its wide area of distribution in the California Coast Ranges. Sandstone and conglomerate occur in lesser amounts. Brownish-yellow sandstone, similar to that common in the Knoxville in the Coast Ranges several hundred miles farther north, occurs on the border of an irregular area of diabase on Tepusquet Creek, in the San Rafael Mountains, and contains the characteristic Knoxville fossil *Aucella piochii* Gabb (Pl. XIII, figs. 1, 2, 3a, 3b, p. 128). The rock is present only in very small patches, and seems to have been brought up from below by the diabase intrusion. The Knoxville was recognized in one other place in the San Rafael Mountains a few miles north of Zaca Lake, at the base of the series mapped as pre-Monterey, where also it contains *Aucella piochii.* It is very likely that a portion of the areas mapped as pre-Monterey belongs to the lower Cretaceous, but it is not probable that the whole does.

PRE-MONTEREY ROCKS.

Two large areas of sedimentary rocks whose age has not been determined otherwise than that they are older than the Monterey occur in the San Rafael Mountains. They are mapped as pre-Monterey rocks. It is probable that strata of Knoxville (lower Cretaceous) age occur at the base of the series in those areas and that the higher portions represent either the upper Cretaceous or the Eocene, or both. Detailed work was left until another time.

The larger of these two areas occupies the northeast corner of the region shown on the map, and is about 60 square miles in extent. The other lies on the northeastern slope of the high ridge north of Zaca Lake. In these areas are exposed a great series of thin-bedded, dark-colored, locally greenish shale alternating with more massively bedded sandstone, which is in places of a very granitic nature. Conglomerate, much of it plainly evidencing its origin from granite, occurs in minor horizons. Knoxville fossils were found in a gritty greenish sandstone near the lowest portion of this pre-Monterey terrane, about 2 miles north of Zaca Lake. The higher portion seems to be the continuation of a formation in San Luis Obispo County that

has been considered upper Cretaceous and of one in southeastern Santa Barbara County that has been ascribed to the Eocene. Its age is therefore much in doubt. It may also include at the top part of the Vaqueros (lower Miocene), which overlies this doubtful terrane and of which the base has not been definitely determined.

Structurally the strata included in this pre-Monterey group lie beneath the Monterey and upper Vaqueros, but though far older they do not bear so strongly the marks of intense folding as do the brittle Monterey shales. They are, however, steeply upturned, and the lines of folding, as in the case of the other formations, are in general in a northwest-southeast direction.

TEJON, SESPE, AND VAQUEROS FORMATIONS, UNDIFFERENTIATED (EOCENE-MIOCENE).

GENERAL STATEMENT.

The Santa Ynez Range is mostly composed of a thick terrane of marine sediments equivalent to a part or all of the Tejon formation and the Vaqueros formation. The former is Eocene and the latter lower Miocene in age. This terrane comprises a continuous succession of marine sediments of detrital origin, seeming to present no point at which an angular unconformity exists, although the line at the base of the coarse conglomerate containing the Vaqueros fossils doubtless marks a long time interval.

In the preliminary report on the Santa Maria district[a] mention is made of the Sespe formation as being represented here, and a small area of it is shown on the map accompanying that report. The Sespe formation belongs to the Eocene or Oligocene and is a distinct formation above the Tejon and below the Vaqueros. It occurs extensively in the Santa Ynez Mountains north of Santa Barbara, and an outcrop of blood-red sandstone in this range 3½ miles south of the Santa Ynez Mission was indicated on the outline map as belonging to the Sespe because of its lithologic resemblance to the typical rocks of this formation. This small area has, however, not been separately shown on the present map, as there is no good proof of its age. It is quite possible that the Sespe formation is represented in parts of this western portion of the range by rocks not recognizable on the lithologic grounds which are deemed sufficient for the determination of this formation in the vicinity of Santa Barbara or the Ojai Valley, to the east; or it may be that sedimentation was not operative in the western part of the range during Sespe time, and therefore that rocks of that age are lacking from the geologic section in this region. The amount of work done in the Santa Ynez Range does not warrant a full discussion of the structure and relations of

[a] Bull. U. S. Geol. Survey No. 317, 1907, pp. 1-69.

its rocks stratigraphically below the base of the Monterey (middle Miocene) shale.

Strata corresponding to the upper portion of the Tejon-Sespe-Vaqueros terrane have been recognized also in the San Rafael Mountains, where they are exposed at the base of the Monterey (middle Miocene), and it may be that the pre-Monterey rocks are in part equivalent to the lower portion of this terrane. The Vaqueros and possibly part of the Tejon are present also in the Casmalia Hills.

LITHOLOGIC CHARACTER.

The lower portion of the terrane is made up of a thick series of greenish-gray coarse and fine sandstones, many of them concretionary in character, interbedded with dark, fine-grained, thin-bedded shales in lesser amount. Toward the middle of the terrane the shale increases in amount, alternating with thin beds of sandstone. Much of the shale has a characteristic olive-gray color, and owing to its hard, gritty, brittle nature it makes excellent road material for the Santa Ynez Valley. The shales and sandstones give place above the middle of the terrane to deposits of shallow-water character—coarse sandstone and a great quantity of coarse, in many places greenish or reddish, gravelly conglomerate. This conglomerate contains abundant Vaqueros fossils and probably represents the base of that formation and a period of shallow-water conditions with which the Vaqueros began. The conglomerate gives place in turn to more shale and sandstone, which continue to the summit of the terrane. At the top there is a conformable gradation into the Monterey (middle Miocene) beds, the summit of the Vaqueros being marked by a calcareous zone in many places—as, for instance, southwest of Lompoc, where the two formations are divided by a very prominent exposure of hard limestone. This limestone is quarried and used in the refining of beet sugar. Sandstone, shale, and conglomerate belonging to the Tejon-Sespe-Vaqueros terrane occur at the seaward end of the Casmalia Hills. They form a series conformably underlying the Monterey (middle Miocene); but they are separated from beds of flint and shale that can be definitely assigned to the latter formation by an intervening horizon many hundred feet thick of soft, light-brown, clayey, alkaline shale that is almost invariably full of crystalline gypsum. Here the conditions existing during the period of transition from typical Vaqueros to typical Monterey sedimentation must have been very different from those prevalent over the areas occupied by the Santa Ynez and San Rafael ranges. Acidic volcanic ash is interbedded with the Tejon-Sespe-Vaqueros strata in the Casmalia Hills. The occurrence of the ash and the alkaline

shale is mentioned by H. W. Fairbanks in the two quotations given under the heading "Previous knowledge of the geology," pages 12–13, and this author discusses them further in his paper there cited.

STRUCTURE AND THICKNESS.

Like all the Tertiary and pre-Tertiary formations of this region the deposits under discussion have been subjected to folding that has left none of them in an undisturbed attitude. But as they consist in large part of soft sandstone and conglomerate with interbedded layers of sandstone and clayey shale, they have not been so violently fractured and disturbed as much of the brittle shale of the lower portion of the Monterey (middle Miocene). The high ridge of the Santa Ynez Mountains from Point Conception eastward is formed by a great monocline in the sandstone of this terrane, dipping toward the sea on the south at an angle of about 30°. North of this ridge occurs a longitudinal depression in the range in which the folds of the beds are rather low; and still farther north, bordering the Santa Ynez Valley, these rocks are considerably disturbed, dipping in various directions and at all angles between 15° and the vertical. The general inclination of the beds on the north side, however, is northward, the structure of this part of the range, broadly viewed, being anticlinal. In the San Rafael Mountains the Vaqueros strata are steeply folded along northwest-southeast lines, in conformity with the overlying Monterey. A marked example of the way in which the soft, coarse conglomerate has been left little affected occurs in Buckhorn Canyon, where thick beds of this rock, probably the basal part of the Vaqueros, lie almost horizontal.

The Tejon-Sespe-Vaqueros rocks have a thickness of at least 5,000 feet in the Santa Ynez Mountains, and further work will probably allow these figures to be considerably increased.

AGE AND FOSSILS.

At least two distinct faunas are found in the Tejon-Sespe-Vaqueros strata. The lower is characteristically Eocene, and similar to that of the Tejon formation of the type locality; the upper contains many of the species found at the type locality of the Vaqueros formation, which is the standard lower Miocene of the central California province. So far as is definitely known no species bridges the gap between these two faunas, either here or elsewhere in California, although the beds containing the two are apparently conformable not only in the Santa Ynez Range but also locally as far north as Martinez, east of San Francisco Bay.

The following tables show the fossiliferous Tejon and Vaqueros localities and the species of fossils found at each. (See map, Pl. I, in pocket; and illustrations of fossils, Pls. XII to XXVI, pp. 126–154.)

Tejon (Eocene) fossils from the Santa Maria district, California.

	4507.	4509.	4513.	4518.
Cardium brewerii Gabb (Pl. XII, fig. 1)	×	......	......	×
Codakia? sp. a	×	......	......	......
Conus cf. hornii Gabb	......	......	......	×
Crassatellites collina Conrad (Pl. XII, figs. 2a, 2b, 3)	×	×	......	×
Dosinia elevata Gabb	×	......	......	......
Fusus occidentalis Gabb	×	......	×	×
Ficus mamillatus Gabb (Pl. XII, figs. 5a, 5b)	×	......	......	×
Glycymeris cf. veatchii Gabb var. major Stanton	×	×	......	×
Mactra cf. uvasana Conrad	......	......	×	......
Meretrix uvasana Conrad	×	......	......	......
Meretrix sp	......	......	×	......
Neverita? sp	......	......	×	......
Nucula truncata Gabb	......	......	......	×
Ostrea idriaensis Gabb (Pl. XIV, figs. 1a, 1b)	×	......	......	×
Pecten (Chlamys) yneziana Arnold (Pl. XII, fig. 4; Pl. XIII, figs. 6a, 6b)	×	×	......	×
Phacoides cumulata Gabb (Pl. XIV, fig. 2)	......	......	......	×
Phacoides (Miltha?) sp	×	......	......	......
Tellina? sp	......	×	......	......
Turritella (martinezensis Gabb var.?) lompocensis Arnold (Pl. XIII, figs. 5a, 5b, 8)	......	×	......	......
Turritella uvasana Conrad (Pl. XII, fig. 6; Pl. XIII, fig. 7)	×	×	......	×
Venericardia planicosta Lamarck (Pl. XIII, fig. 4)	×	......	......	×

4507. Just above San Julian ranch house, 1 mile southeast of bench mark 603.
4509. Sharp turn in road in San Miguelito Canyon, 4½ miles S. 20° W. of Lompoc bench mark 95.
4513. South side of El Jaro Creek road, one-half mile west of bench mark 927.
4518. Three miles north of Sudden, on north flank of 1,912-foot hill.

Vaqueros (lower Miocene) fossils from the Santa Maria district, California.

	4478.	4504.	4508.	4510.	4511.	4512.	4514.	4516.	4517.	4519.	4520.	4521.
Balanus cf. estrellanus Conrad	......	......	......	......	......	......	......	......	×	......	×	......
Cardium aff. quadrigenarium Conrad	......	×	......	......	......	......	......	......	×	......	......	......
Chione cf. mathewsonii Gabb	......	......	......	......	......	×	......	......	......	......	......	......
Conus sp	......	......	......	......	......	......	×	......	......	......	......	......
Crassatellites (?) sp	......	......	......	......	×	......	......	......	......	......	......	......
Gasteropod, genus and species indet	......	......	......	......	......	......	......	×	......	......	......	......
Meretrix (?) sp	......	......	......	......	......	......	......	×	......	......	......	......
Modiolus yneziana Arnold (Pl. XV, fig. 2)	......	×	......	......	......	......	......	......	......	......	......	......
Mytilus cf. mathewsonii Gabb	......	......	......	......	......	......	......	......	......	......	×	×
Ostrea eldridgei Arnold (Pl. XVI, fig. 2; Pl. XVIII, figs. 6a, 6b)	×	×	......	×	......	......	×	......	......	......	......	×
Ostrea, new species, near titan Conrad	......	×	......	......	......	......	......	......	×	......	......	×
Pecten vanvlecki Arnold (Pl. XVII, figs. 1, 2)	×	......	......	......	......	......	......	......	......	......	......	......
Pecten (Lyropecten) bowersi Arnold (Pl. XVIII, fig. 5)	......	......	......	......	......	......	......	......	......	......	......	×
Pecten crassicardo Conrad (Pl. XVIII, fig. 1)	......	......	......	......	......	......	......	......	......	......	......	×
Pecten lompocensis Arnold (Pl. XVIII, figs. 2, 3, 4)	......	......	......	......	......	......	......	......	......	......	......	×
Pecten magnolia Conrad (Pl. XVI, fig. 1)	×	×	×	......	×	×	......	......	×	×	×	......
Pecten sespeensis var. hydei Arnold (Pl. XVII, fig. 3)	×	......	......	......	......	......	......	......	......	......	......	......
Solen sp	......	......	......	......	......	......	......	×	......	......	......	......

Vaqueros (lower Miocene) fossils from the Santa Maria district, California—Continued.

	4478.	4504.	4508.	4510.	4511.	4512.	4514.	4516.	4517.	4519.	4520.	4521.
Terebratalia kennedyi Dall (Pl. XVII, fig. 4a, 4b, 4c, 4d)												×
Purpura vaquerosensis Arnold (Pl. XV, figs. 1a, 1b)		×										
Turritella sp. indet			×									
Turritella ineziana Conrad (Pl. XVI, fig. 3)							×	×	×			
Turritella variata Conrad (young?)								×				

4478. Two miles south of Santa Ynez, on knoll just east of mouth of Ballard Canyon.
4504. Three-fourths of a mile up ridge northeast of San Julian ranch house, 1¼ miles east of bench mark 603.
4508. El Jaro Creek, one-fourth mile east of Salsipuedes Creek, southeast of Lompoc.
4510. Five miles north of Concepcion, one-fourth mile west of mouth of Escondido Creek.
4511. Float on hillside along east side of Los Amoles Creek, 1 mile above El Jaro Creek.
4512. Ridge between Los Amoles and Salsipuedes creeks, 10½ miles S. 33° E. of Lompoc bench mark 95.
4514. About 10 miles west of Santa Ynez, on south bend of river 1½ miles southeast of bench mark 552.
4516. South of Santa Ynez Mission, 2½ miles up Alisal Creek, at mouth of valley on east.
4517. Three miles north of Sudden, on north flank of 1,912-foot hill, above locality 4518, which is Eocene. (See p. 29.)
4519. On ridge 2 miles east-southeast of El Jaro Creek, bench mark 603, one-half mile west of 1,111-foot hill.
4520. West side of ridge between Los Amoles and El Jaro creeks, 1 mile west of bench mark 603.
4521. Lime quarry 5 miles southwest of Lompoc.

MONTEREY SHALE (MIDDLE MIOCENE).

GENERAL STATEMENT.

A great series of fine shales, largely of organic origin, overlies conformably the coarse and fine sedimentary deposits of the Vaqueros. These shales make up the Monterey formation and are probably representative of the whole of middle Miocene time. The series is of great thickness and is doubly important as the probable source and the present reservoir of the oil. The areal extent of the Monterey is not adequately represented on the map. It doubtless covers as one continuous sheet the whole basin between the Santa Ynez and San Rafael mountains, as well as a large part of these ranges, but it is concealed over considerable areas by later deposits, which are in many places very thin. The character, structure, and relations of the Monterey have been the chief subject of the present study.

The name Monterey was given by William P. Blake[a] in the early fifties to an organic shale formation typically developed near Monterey, in central California. It is very extensive in the California Coast Ranges, being the "bituminous shale" described by Whitney[b] as occurring at widely separated points north and south of the Golden Gate. Its age is generally taken as middle Miocene. It is the source of much of the petroleum found in California. The shale characteristic of this unique formation is not similar to ordinary clay shale, but is composed largely of the remains of minute marine organisms. In an

[a] Proc. Acad. Nat. Sci. Philadelphia, vol. 7, 1855, pp. 328–331.
[b] Geological Survey of California, Geology, vol. 1, 1865, p. 137.

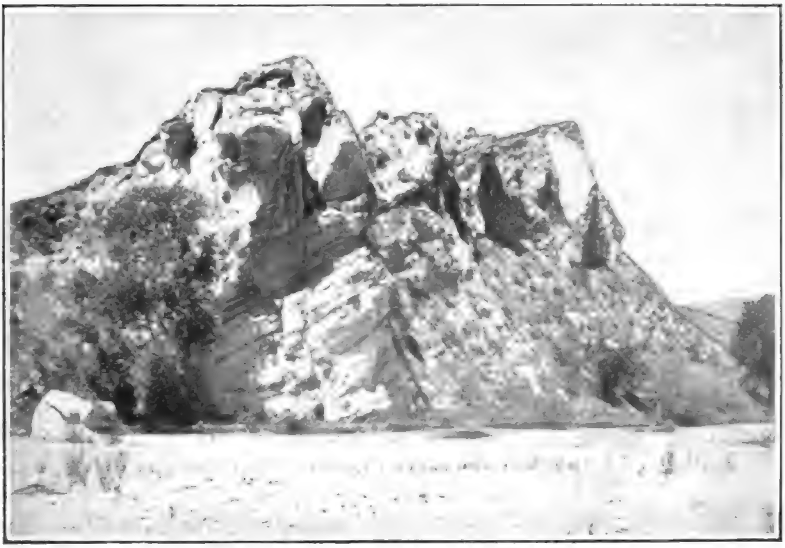
unaltered condition it resembles chalk, but is of siliceous instead of calcareous composition.

The Monterey in the part of California treated here may be divided on lithologic grounds into two parts, although there seems to be perfect conformity throughout the series. There is no definite dividing line to be drawn, but taken as a whole the lower half, composed chiefly of hard, metamorphosed, in places flinty shales, is distinct from the upper half, in which soft shale, giving evidence to the naked eye of its organic origin, is predominant.

LOWER DIVISION.

The fossiliferous limestone at the top of the Vaqueros is overlain conformably by hard calcareous and flinty unfossiliferous shale characteristic of the base of the Monterey. In places the limestone at the top of the Vaqueros is not well developed, but is replaced by a series of thin-bedded, in the main fairly hard, siliceous, calcareous, and somewhat argillaceous shales of coarse and fine texture, in which no well-defined line of demarcation between the two formations is to be drawn. The Vaqueros and Monterey terranes taken as wholes are distinct units, representing periods of deposition of entirely different character. As indicated by the rocks, deposition was continuous between the Vaqueros and Monterey and the change in character came suddenly, although less so in some places than in others. The general nature of the Vaqueros series is detrital; that of the Monterey is organic. The former contains many well-preserved molluscan forms, the latter few. Close to the line between the two, beds predominatingly of a gravelly or sandy nature or those bearing fossil mollusks are considered part of the Vaqueros; those of a fine texture and of flinty or opaline or chalcedonic nature, part of the Monterey.

Above the transitional limestone horizon between the Vaqueros and Monterey the lower half of the latter formation consists of a thick series of thin-bedded, hard, brittle, siliceous and calcareous shales, with local gradations on the one hand into beds of the hardest flint and on the other into soft diatomaceous earth. Near the base there is usually a horizon of black, brownish, or wax-colored flint in heavy beds one to several feet thick, and similar massive beds of peculiar sand-colored limestone with characteristic lamellar weathering. The greater part of the series is made up of brittle siliceous shale, usually much fractured and rather commonly crumpled, in beds averaging about one-half to 1 inch in thickness, in places alternating with thin shaly calcareous beds or massive strata of limestone. Pls. III, *B*, and VI, *B* (p. 46), show outcrops of typical flinty shale of the lower division. Beds of flinty shale or of pure flint are included here and there. The flint is of different colors—amber, black, milky, red, brown, etc.—and of different degrees of translucency. Much of it has been fractured and recemented with chalcedonic veins.



A. CHARACTERISTIC EXPOSURE OF VOLCANIC ASH NEAR BASE OF MONTEREY FORMATION.

At point where Cuyama River enters the Santa Maria Valley. Photograph by Ralph Arnold.

B. UPTURNED AND CONTORTED SEMIFLINTY MONTEREY SHALE.

On Sisquoc River, 5 miles east of Sisquoc. Heavy oil is exuding at a point immediately to the right of the man. Photograph by Ralph Arnold.

It is in some localities banded with fine white laminæ or with bands more translucent than the rest. These bands run parallel with the bedding, and commonly show intricate contortions. The flint fractures conchoidally. From the flint there is every step in the gradation through rocks of less hardness and flinty, compact character to soft white diatomaceous shale. The soft unaltered shale in which the constituent diatom tests are plainly to be seen occurs sparingly, however, in the lower division. A striking example of its occurrence at that horizon can be found at the very base of the Monterey on the San Julian ranch, at the junction of El Jaro and Salsipuedes creeks, where it is pure, soft diatomaceous earth in thick beds, associated with flint and lime and overlying the hard fossiliferous, calcareous conglomerate of the Vaqueros. The specimen of analysis 3 (p. 45) is from this point. The varieties of shale are very numerous, but there is no departure from the general siliceous and calcareous types so peculiar to this formation. There is no common clay shale or slate derived from it, and only very locally is there an appearance of a sandy texture. In the San Rafael Mountains the series has a somewhat different character, especially at the base, where a considerable amount of sandstone, in some places soft and in others quartzitic, is interbedded with the hard calcareous shales. Hard, coarse, yellow and grayish volcanic tuff of acidic nature is interbedded with the Monterey in the vicinity of Cuyama River (see Pl. III, *A*), and elsewhere the lowest portion of the formation is marked by beds of tuff of local extent. At the east end of the Santa Rita Hills the Vaqueros grades into the Monterey through beds of coarse basic tuff composed of small fragments of glass and crystals of various kinds and of large fragments of pumice. Round bowlders or nodules of very fine grained basalt that look like volcanic bombs are included in this tuff.

The series of hard shales of the lower division is commonly impregnated with bituminous material. The limy beds have almost universally a bituminous odor and some of them contain pockets of tarry oil. The same is true of the flint with the difference, however, that the limestone is impregnated with petroleum, owing to its porosity, whereas the oil in the compact flint seems more commonly to be contained along lines of fracture or in cavities. The great mass of the hard, brittle shales has in general a similar odor or is discolored with oil. This hard shale series, especially the lower portion of it, and in places possibly the uppermost sandstone of the formation just below it, contains the principal oil-bearing zones in the developed fields. The fact that this shale is so brittle and fractures when folded has an important bearing on the storing of oil in this portion of the Monterey. The fracturing produces cavities in which the oil can collect while the softer unfractured shales adjacent remain more or less impervious to the oil.

UPPER DIVISION.

The line of division between the lower and upper portions of the Monterey is rather arbitrary, yet if each portion is taken as a whole the lithologic distinction is marked, and the separation is made natural by the areal limitations of the outcrops of one or the other in various places. Where they are in contact a conformity between the two halves of the formation is evident and a gradation occurs from the porcelaneous and flinty shales of the lower part into the light-colored, earthy beds of the upper. Such is the occurrence, for instance, near the north edge of the hills 4 miles west-southwest of the town of Lompoc.

The greater part of the upper division is made up of white or light chocolate-colored diatomaceous shale, usually of light weight and porous, but grading in places into heavier and harder, more compact, brittle, porcelain-like shale. The soft shale is extremely fine grained, rarely being at all gritty. The bedding is characteristically very thin, but where great masses of the soft white shale, which goes by the name of diatomaceous earth, occur, lines of bedding are usually indistinguishable, except here and there on thin projecting laminæ produced by weathering, or on the upper surface of small cavities due to the eating out of less resistant patches. Pl. IV illustrates two characteristic types of the soft unaltered shale. In the upper view it is massive, and bedding planes are almost indistinguishable except for lines brought into relief by weathering and erosion. In the lower view it is slightly more compact and lies in distinct platy layers. Major bedding planes from a fraction of an inch to several inches apart are distinctly apparent, and there is a further laminated structure that enables the shale to be split into plates of extreme thinness. An artificial cut through somewhat disintegrated shale of the upper part of the Monterey is shown in Pl. VIII, *A* (p. 78). The typical unaltered diatomaceous shale is pictured in Pl. V, *A*. The small round diatom tests of which it is largely composed are faintly distinguishable with the naked eye in the photograph. In general, both the softer and harder varieties of the Monterey shale, owing to their siliceous composition, do not give way readily to decomposition or weathering. Local chalcedonic lenses are to be found in this series roughly following the bedding planes in unaltered shale, as well as horizons of hard, porcelaneous, usually much-fractured shale; but the latter does not become predominant over the softer shale as it does in the lower division.

The white chalklike deposits of this formation are not fully described by the use of the word shale in its ordinary sense. Especially in the massive deposits, where bedding is not very apparent, it has neither in composition nor lamination the character of ordinary shale. But this word has come into use in connection with the Monterey for lack of any other. The major portion of the formation, however, does

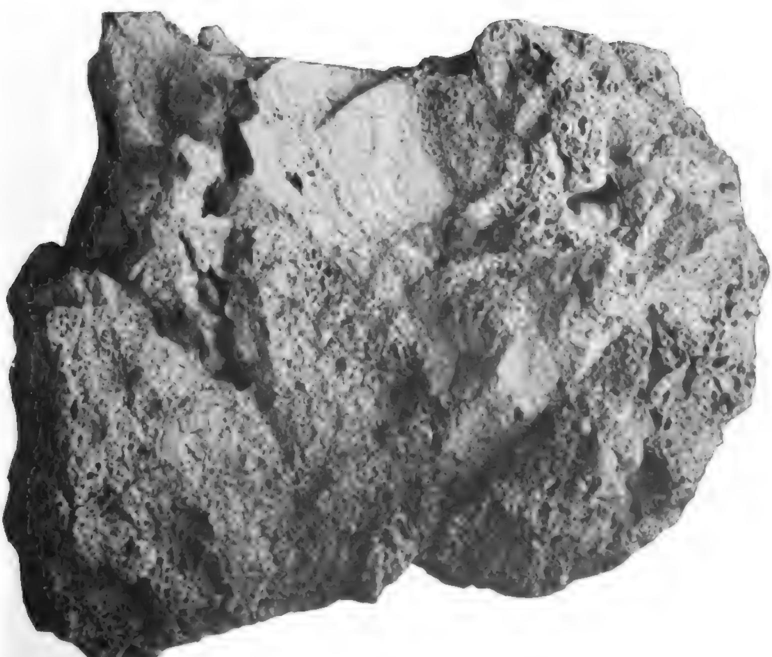
A

B

SOFT WHITE DIATOMACEOUS SHALE.

A. Characteristic exposure north of Casmalia. *B*. Detail of weathering at Burton Mesa, east of Pine Canyon. Photographs by Ralph Arnold.

A



B

DIATOMACEOUS SHALE.

A. Typical soft, white, unaltered specimen. *B*. Red, brittle, and heavy specimen; metamorphosed by the burning of its hydrocarbons.

resemble shale in its thin stratification, the great difference being in the siliceous instead of argillaceous composition. Locally there are beds of clayey nature in the upper division which form a connecting link between the "chalk rock," as the diatomaceous shale is colloquially termed, and common clay shale. Characteristic oval and lenticular yellow concretions of hard lime are commonly included in the shale of the upper division. They range in diameter from a few inches to 2 feet or more. In many places they occur at irregular intervals and of irregular size along a bedding plane, locally displacing the ordinary shale and interrupting the continuity of not merely one bed but many thin beds. They are invariably elongated parallel with the bedding.

Volcanic ash is interbedded with the soft shale of the upper division in the hills immediately south of Lompoc. It is very fine grained, soft, and uncompacted, and probably corresponds in composition to rhyolite. It somewhat resembles the pulverulent diatomaceous earth, but is easily distinguishable by its grayish color and grittiness.

The upper portion of the Monterey, like the lower, is to a large extent impregnated with bituminous material. It is apt almost anywhere in this region to give out a bituminous odor when broken into or to show a brownish discoloration due to the presence of oil. In places the shale, otherwise white, is specked with minute black spots of bitumen. Thin sandy layers occur sparingly interbedded with the shale, and these almost without exception have absorbed considerable oil and have a dark-brown color and strong odor. But these beds of sand are very rare and make up no appreciable proportion of the series.

The soft varieties of the Monterey shale are almost invariably alkaline and have a salty taste. They contain an abundance of salts easily soluble in water that form characteristic wooly coatings of efflorescence on the surface of outcrops. This is especially true near the summit of the formation, where a soft claylike gypsum-bearing shale locally marks the contact with the Fernando above. This gypsum is crystallized in plates along seams and bedding planes much like the gypsiferous clay of the Casmalia Hills, which is supposed to be Vaqueros in age. Zones of gypsiferous shale occur also at other places in the upper division of the Monterey, but it is not known whether there are any single horizons at which it is constant. Where the gypsum occurs the shale is usually of more argillaceous character and bears a closer resemblance to ordinary clay shales. The significance of this alkalinity in the Monterey is unknown. The organic shale is considered to be of marine origin in fairly deep water, and owing to the almost complete absence of all but the finest grained detritus the alkalinity can not be considered as proof of shallow-water or brackish-water origin. The salts may have some relation to the chemical changes involved in the production of petroleum.

DIATOMACEOUS EARTH DEPOSITS.[a]

The infusorial earth, diatomaceous earth, diatomaceous shale, or tripoli, as the same material is variously called, of which the upper division of the Monterey is chiefly composed, is of fairly pure quality in this region and of considerable economic value, especially as it occurs in inexhaustible quantities close to transportation facilities. The areas of it are extended and the series of strata very thick. Deposits suitable for working occur in the hills immediately south of Lompoc; southwest and west of Lompoc; along the river east of Lompoc; in the northeastern and southeastern portions of Burton Mesa and over the Purisima Hills east of it; over wide areas in the Purisima Hills southwest, south, and southeast of Los Alamos; on the southern flanks of the Santa Rita Hills; 1½ miles north of the Santa Ynez Mission; in smaller amounts near the east edge of the area mapped, a mile north of Santa Ynez River; underlying the San Antonio terrace south of Casmalia; over a wide region southeast, east, and north of Casmalia; on Graciosa Ridge, and in the region extending from the head of Howard Canyon to a point southeast of Sisquoc. The uses to which this material can be put are numerous and the demand for it is increasing.

COMPOSITION OF THE MONTEREY SHALE.

MATERIAL OF SHALE.

The composition of the Monterey shale is of especial interest. One is able to see on examining the soft unaltered variety with a hand lens, or sometimes even with the naked eye, that it is full of small round dots ranging, to speak roughly, from 0.1 mm. to 1 mm. in diameter. These are the skeletons of minute marine organisms called diatoms. They are a low order of plants or algæ having a framework of silica. They are locally so closely packed together that they seem to form the bulk of the deposit. In some of the rock they are so well preserved that the details of their structure can be made out with the aid of higher magnification. But elsewhere they appear crushed and almost unrecognizable. It is a question how much of the shale is formed of the diatom frustules that have been thus crushed. The shale in which the remains are well preserved and abundant is extremely soft and white and may be rubbed at a touch into a powder like flour. The round diatom disks are white and soft just like the matrix surrounding them, which looks as if it, too, were made up of diatom remains that had preserved their form less perfectly. Shale in which the remains are less prominent has

[a] A more extended description of these diatomaceous deposits is published in "Contributions to Economic Geology, 1906" (Bull. U. S. Geol. Survey No. 315, 1907, pp. 438–447), under the title "Diatomaceous deposits of northern Santa Barbara County, Cal."

the same appearance, as if formed of the same materials, but compacting and crushing seem to have gone a little further so as to obscure the organic remains. Almost all the shale of the upper division of the Monterey contains diatom remains where it has not undergone alteration into the hard varieties. The same is true of the soft shale wherever it occurs in the lower portion of the formation, the most notable example being at the very base of the Monterey on the San Julian ranch east of the junction of Salsipuedes and El Jaro creeks, where it is associated with hard flint and limestone immediately overlying the fossiliferous limestone and conglomerate of the Vaqueros. There the shale is earthy, pure white, and full of diatoms.

When the shale has undergone alteration and hardening into the porcelaneous and flinty varieties the constituent organic remains are usually obscured, but here and there even in these the impressions may be found preserved. Usually an examination under the microscope reveals scattering circular and oval areas, of slightly different composition or character from the surrounding rock, that look as if they might represent the forms of organisms. In speaking of the exposure of Monterey rocks between the mouth of Schumann Canyon and Lions Head on the southern flank of the Casmalia Hills, H. W. Fairbanks says:[a] "The basal portion of the series is composed chiefly of clear, flinty rocks, showing abundant remains of organisms visible to the unaided eye." And in speaking of the harder varieties of Monterey shale in general of the Point Sal region he says:[b] "When examined with the hand lens much of the rock is seen to be thickly specked with little round dots, averaging, perhaps, a millimeter in diameter. Under the microscope * * * the circular areas did not appear as numerous as in the hand specimen, and were only faintly distinguished by clearer polarization."

Aside from the diatoms the rocks of the Monterey contain remains of minute Foraminifera, which have calcareous frames, and Radiolaria, which secrete silica to form their tests. The latter are present sparingly. The common siliceous shale contains very little lime and no Foraminifera have been found in it in this district, although they have been reported from the typical Monterey shale elsewhere. R. M. Bagg[c] found 66 species belonging to 17 genera in chocolate-colored, soft, fine-grained shale of the same formation near Asuncion, San Luis Obispo County. J. C. Branner in the introduction to Bagg's paper, describes the shale as follows: "The shale proper also varies; at some places it is flinty, at others it is somewhat sandy, and at still others it is soft and chocolate-colored, and contains an abundance of well-preserved Foraminifera. * * * The bulk of

[a] Geology of Point Sal: Bull. Dept. Geology, Univ. California, vol. 2, No. 1, 1896, p. 9.

[b] Op. cit., p. 10.

[c] Miocene Foraminifera from the Monterey shale, California: Bull. U. S. Geol. Survey No. 268, 1905.

this shale is made of diatom skeletons. * * * Even when the rocks are flinty they often contain good impressions of Foraminifera." Foraminifera occur in the partially calcareous shales of the Santa Maria district, and in places the limestone is full of them. In some specimens they are perfectly preserved and various kinds may be easily seen with the unaided eye. In other places the limestone shows no trace of organisms; but it is the opinion of the writers that they have been present in such places and have lost their shape, and that foraminiferal skeletons account for a large part of all the Monterey limestone and for the calcareous portion of the limy shales. H. W. Fairbanks says in his paper quoted on page — that the limestone of the Point Sal region "appears to be formed almost exclusively of minute organisms."

Specimens representing different varieties of the Monterey shale and flint were sent to F. J. Keeley, of the Philadelphia Academy of Natural Sciences, who very kindly made examinations of them and reported regarding their diatom contents. (See Pls. XIX and XX.) He found diatoms plentiful in the unaltered earthy shale and less common in the more compact shale and in the less pure, either gritty or argillaceous shale. Sponge spicules were common in all the samples, and in those last mentioned they were more abundant than diatoms. No examination was made of the indurated varieties. Mr. Keeley was unable to make more than a hasty examination, but on request he estimated roughly that the purest material contained from 5 to 10 per cent of diatoms and that the soft shale in which fewer could be seen contained possibly 1 per cent. He found a few Radiolaria but no Foraminifera in the pure siliceous shale, diatoms and next to them sponge spicules being by far the predominant organic remains.

C. S. Boyer, of the Philadelphia Academy of Natural Sciences, kindly identified the species of diatoms in two slides prepared by Mr. Keeley from the two purest samples of diatomaceous earth that were sent to him. Mr. Keeley says: "The lists made by Mr. Boyer cover only the species he saw in the slides sent him, and an exhaustive examination of the material, which would require searching over, say, a hundred slides or more, would probably give a long list of species, many of which might not be seen more than once or twice in the course of such an examination." Nevertheless, these lists probably indicate the commonest species. In the slide made from the shale at the base of the Monterey from the locality above referred to at the junction of Salsipuedes and El Jaro creeks Mr. Boyer found the following diatoms:

Coscinodiscus marginatus Ehrenberg.
Coscinodiscus marginatus var. intermedia Rattray.
Coscinodiscus robustus Grev.
Arachnodiscus (fragment).
Diploneis? (fragment).
Melosira sulcata Ehrenberg (rare).

Mr. Boyer says: "The deposit consists almost entirely of *C. marginatus* and *C. robustus* of various sizes and often without rims. It is impossible, in certain cases, to distinguish between these two forms. The variety *intermedia* is between the two and was created by Rattray."

The second slide was made from soft shale of the uppermost portion of the Monterey, from the Pinal property on the east side of Pine Canyon, on the north flank of Graciosa Ridge. The following diatoms were found:

Coscinodiscus oculus iridis Ehrenberg (abundant) (Pl. XI, fig. XIX).
Coscinodiscus marginatus Ehrenberg.
Coscinodiscus marginatus var. intermedia Rattray.
Coscinodiscus robustus Grev. (Pl. XX, fig. 4).
Coscinodiscus radiatus Ehrenberg.
Coscinodiscus obscurus A. S. (Pl. XX, fig. 2).
Coscinodiscus nodulifer Janisch.
Coscinodiscus heteroporus Ehrenberg.
Coscinodiscus subtilis Ehrenberg (Pl. XX, fig. 3).
Actinoptychus undulatus Ehrenberg (rare) (Pl. XX, fig. 1*a*).
Arachnodiscus ehrenbergii var. californica (fragment).
Lithodesmium cornigerum Brun. (Pl. XX, fig. 1*b*).

According to Mr. Boyer this second sample consists chiefly of fragments of *Coscinodiscus oculus iridis* Ehrenberg, which is a larger and more delicate form than the one predominating in the first, and both he and Mr. Keeley comment on the peculiar absence of it there. The difference in the fauna in these different localities is of interest, inasmuch as the deposit represented by the first slide was at the base of the Monterey and that represented by the second near its summit.

Besides the small organisms that have been described as forming a portion of the shale material, and the less abundant organic remains mentioned on pages 42–43, the deposits of Monterey age contain a considerable percentage of fine siliceous and aluminous matter, probably of detrital origin, in the shape of exceedingly minute clastic grains. The chemical analyses of specimens from different localities show a large percentage of alumina, the presence of which is probably the result of fine argillaceous silt settling on the sea bottom to aid in the formation of the shale. The origin of the silica is more in doubt. There is no question of the presence of a large amount of siliceous diatom skeleton material, and the many fine-rounded and angular particles of quartz revealed by the polarizing microscope in the unaltered shale indicate that the sediments derived from shore areas carried quartz grains also, but there is no proof as to which of these sources supplied the bulk of the silica, of which the shale is mostly composed. Besides the recognizable diatom remains it is impossible to tell how much of the shale is composed of similar skeletons that have been crushed beyond any semblance of their original form. Comparatively few forms are perfectly preserved, most of

those observed under the microscope being only fragments, and this makes it probable that others are still more fragmentary and in a state of complete demolition. The likelihood, therefore, is that a greater proportion of the pure shale than 5 to 10 per cent, as roughly estimated by Mr. Keeley on the basis of visible forms, is composed of silica derived from diatoms. Radiolaria, which are scattered through the shale sparingly, have contributed somewhat to the organic silica. Whatever conclusion one should come to would apply to almost all of the soft unaltered shale of the siliceous type in the Monterey of the Santa Maria district, as this type is fairly constant. Locally it is varied by an increased proportion of argillaceous material, causing a greater similarity in appearance to ordinary clay shale, or by the presence of lime; but diatoms are visible in practically all of it and the general conditions of deposition seem to have been the same throughout. The conclusion is reached elsewhere (p. 47) that the same probable origin may be assigned to all the siliceous shales of the Monterey, whether hard or soft—or, in other words, to by far the greater part of the formation.

The list of organic constituents of the shale is by no means exhausted by the small organisms of low order so far mentioned. Another important source of silica lies in the abundant sponge spicules, which are only second in number to the diatoms and which are scattered with remarkable persistency throughout the shale. In the slightly gritty beds of soft shale, which occur sparingly, these spicules even predominate over the diatoms, being possibly the cause of the grittiness. They seem also to be less easily obliterated than the fragile diatom shells and to have been preserved in places where slight alteration of the rock has destroyed the latter. One of the commonest and most characteristic features of both the unmetamorphosed siliceous and the calcareous shales is the presence of scales of fish, showing that fish remains found their way to the ooze at the ocean bottom in greater or less abundance. Locally the bones and nearly complete skeletons are also to be found. Delicate mollusk shells, usually of small size, are gathered thickly in some places in the Monterey shale, and at such points may be considered as constituting an appreciable proportion of the total volume of the deposit. As a rule they are crushed and poorly preserved, a fact that lends weight to the theory that a large part of the diatom frustules also have been destroyed. But mollusks are rare in the formation as a whole. Crab shells and claws are occasionally found, usually not whole but in small pieces, as if they had been subjected to conditions favorable to their destruction before coming to rest. Seaweed impressions are not rare. In addition to organic remains of these kinds, the shales, especially the

less purely siliceous varieties, are usually full of small brown scales, spines, and fragments or impressions of nondescript shape which are of organic origin but which can not be recognized as belonging to any particular forms. Here and there, also, large bones are embedded in the deposits. They seem to be those of whales or other large marine vertebrates.

Taken as a whole, the Monterey shale may well be called an organic formation. The practically complete absence of coarse sediments derived from erosion and the abundance of fossil organisms, especially of siliceous skeletons, make it different both in appearance and composition from any other known formation of comparable thickness. The unaltered siliceous shale most nearly resembles chalk, but it contains only a small proportion of lime. Whether or not the organic remains compose more than half or as much as half of the deposit can not be stated.

MICROSCOPIC APPEARANCE.

Under the polarizing microscope little can be made out regarding the structure of the main mass of the soft shale and compact white shale. The groundmass seems to be made up of amorphous colloidal silica surrounding minute grains which are both crystalline and amorphous, but the character of which can not be recognized. Embedded in this are numerous imperfectly angular or more rarely partially rounded crystal particles, probably of quartz. Many of the latter look as if they were due to secondary development rather than originating as clastic grains.

In the more flinty varieties the rock appears to have undergone partial and local crystallization of the silica throughout its mass. In the flint, in which there are alternating, usually crumpled bands of opaque light-colored flint and clear amber-colored or black flint, the opaque bands are composed mainly of amorphous material like that of the softer shale, but in a much more compact state, and the translucent bands are mainly crystalline aggregates. The opaque bands include crystalline particles and, locally, patches of crystal grains like those of the clear flint, and they are included longitudinally by intermittent bands of the clear flint. Furthermore, they are in many specimens of a patchy appearance, parts being less amorphous than others. The bands of the clear flint are composed chiefly of small grains of crystalline quartz, and these are surrounded by a finer grained aggregate of crystalline and amorphous particles. The quartz grains have neither the rounded outlines of waterworn grains nor angular crystalline outlines, but are branching, and appear more like growths. Angular patches of the amorphous silica, many of them showing signs of

incipient crystallization, are included in the clear bands, giving a brecciated appearance. The bands are parallel with the bedding planes. They are commonly followed and more rarely crossed by veins of quartz crystals.

The limestone is made up of granules of crystalline calcite, or calcite showing the beginnings of crystallization. Included in this extremely fine grained, uniform groundmass are larger but yet very small, irregular grains of crystalline calcite, and in places long spicules of the same. In some specimens the granules are more minute than in others and the included larger grains are fewer. In still others, crystallization has entirely altered portions into patches of large, intergrown crystals, leaving angular, unchanged patches sharply marked off, and thus giving an appearance like that of a breccia. The flinty calcareous shale has a minute granular texture, quartz grains both crystalline and semicrystalline being associated with those of calcite. The rock usually has light and dark bands parallel with the bedding, the light bands containing more quartz and having the calcite granules less close together than the darker bands.

CHEMICAL COMPOSITION.

The subjoined table comprises analyses of different specimens and varieties of Monterey shale from the Santa Maria district, with one (No. 5) here included for comparison, of a sample of white bituminous shale from the type locality of the formation at Monterey, farther north on the California coast.

The first three represent typical examples of the unaltered diatomaceous shale of the Monterey. Nos. 3 and 2, respectively, are analyses of the same samples that were found to be rich in diatoms when examined in slides 1 and 2 by Messrs. Keeley and Boyer, as mentioned on pages 40–41. Nos. 4 and 6 are analyses of samples from the same hand specimen, taken within 1 inch of each other, No. 4 showing the composition of unaltered white shale in which diatoms are visible, and No. 6 of the translucent, brittle, flintlike product of extremely local alteration. The next four indicate gradations in the products of the metamorphism. The last analysis (No. 11) represents limestone typical in lithologic appearance of the limestone of the Monterey.

Analyses of Monterey shale.

	Diatomaceous shale.					Flinty shale.					Limestone.
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
SiO_2	65.62	72.50	83.19	80.59	86.89	92.88	86.92	92.37	97.02	98.1	....
Al_2O_3	....	11.71	....	....	2.32	....	4.27	2.46	....	Not det.	....
Fe_2O_3 (total iron)	....	2.35	....	....	1.28	....	....	....	....	Not det.	....
CaO	....	.32	....	....	1.43	....	1.60	1.70	....	....	27.86
MgO	....	.83	....	....	Trace.	....	Trace.	....	....	....	16.64
Alkalies ($Na_2O.K_2O$)	....	1.88	....	....	3.58	....	2.48	....	....	....	....
Ignition	11.00	9.54	....	....	4.89	....	5.13	2.74+ CO_2	....	....	....
	....	99.13	....	....	100.39	....	100.40	99.27	....	....	....

1. Soft, white diatomaceous shale; Purisima Hills, 3½ miles southwest of Harris, Santa Barbara County, Cal. Analyst, W. T. Schaller, 1907.
2. Soft, white diatomaceous shale; Graciosa Ridge, 3 miles southeast of Orcutt, Santa Barbara County, Cal. Analyst, W. T. Schaller, 1907. Approximate analysis.
3. Soft, white diatomaceous shale; San Julian ranch, at junction of El Jaro and Salsipuedes creeks, Santa Barbara County, Cal. Analyst, E. C. Sullivan, 1907.
4. Soft, white diatomaceous shale; San Antonio terrace, 2 miles south of Casmalia, Santa Barbara County, Cal. Analyst, E. C. Sullivan, 1907.
5. White shale; Monterey, Monterey County, Cal. Lawson, A. C., and Posada, J. de la C., Bull. Dept. Geology, Univ. California, vol. 1, 1893, p. 25. Specific gravity, 1.8–2.1.
6. Gray, glassy porcelain shale; from same hand specimen as No. 4. Analyst, E. C. Sullivan, 1907.
7. White porcelain shale; region of Point Sal, Santa Barbara County, Cal. Analyst, H. W. Fairbanks, Bull. Dept. Geology, Univ. California, vol. 2, No. 1, 1896, p. 12.
8. Opaque flint; Point Sal, Santa Barbara County, Cal. Analyst, H. W. Fairbanks, loc. cit.
9. Hard, black, clear flint; 1½ miles west of Zaca, Santa Barbara County, Cal. Analyst, E. C. Sullivan, 1907.
10. Hard, black, clear flint; Point Sal, Santa Barbara County, Cal. Analyst, H. W. Fairbanks, loc. cit.
11. Bituminous limestone; Redrock Mountain, northeast of Lompoc, Santa Barbara County, Cal. Analyst, George Steiger, 1907.

ALTERATION.

The differences in character and composition between the soft and hard varieties of the Monterey shale have been brought out in the foregoing discussion. The question arises, To what are these differences due? It is difficult to give a decisive answer. The main differences in the gradations from the soft to the hard shales lie in the siliceousness, compactness, hardness, and degree of crystallization. Taken as a whole the lower division is made up largely of hard shale and the upper of soft shale, but gradations from one variety to another within an extremely small space occur in both divisions. In some places a thick series of beds of similar character is marked off from a series of different character. Elsewhere a variation occurs bed by bed, or, in still other places, a single bed or lens of shale of one variety is included within another kind. The softer varieties contain at many points small lenses of hard, brittle, or semiflinty shale elongated parallel with the bedding, or strata in which lenses are strung along at irregular intervals, or single small beds composed entirely of harder material. In such occurrences there seems to be a gradation from one variety to the other, and the outlines of the hard layers are not regular or very definite. For example, the diatom-bearing shale of chemical analysis No. 4 and the glassy

opaline rock of analysis No. 6 were samples taken from the same hand specimen within 1 inch of each other. The mass of the deposit from which the specimen came was soft white shale belonging high in the formation and contained a rough layer, a few inches thick, of the harder material between two beds of the soft rock.

The soft shale has been described in the preceding pages as "unaltered," and in referring to the harder varieties different degrees of "alteration" have been mentioned, for the reason that the best explanation of the origin of the harder rocks appears to be that they are products of metamorphism of the soft variety. It is believed that the soft white and chocolate-colored organic shale represents the original state of the beds of the whole formation, and that a process of silicification and crystallization has caused the changes, this process having been aided possibly by structural disturbances and pressure. The beds of soft shale are usually found in attitudes only gently disturbed, whereas the harder shale is most commonly much folded and is invariably the component rock of folds where the forces have been especially intense. This fact may throw light on the problem of the alteration of the shale, and yet it may be simply the outcome of the removal of the softer portion of the formation in the regions of greatest uplift and disturbance. The chief agent in causing the change was probably infiltrating water carrying silica in solution. In some places the process may have been simply or largely infiltration in the extremely porous original shale and deposition of silica in the interspaces, thus giving rise to hardened and compacted irregular granular aggregates of the original amorphous silica and the new crystalline silica combined, the result being an increase in the total percentage of silica. In more extreme cases the original material was probably partly taken in solution and redeposited, being replaced almost entirely along bands or in spots, and the change being carried to a less extent along other layers and in other areas, or else the replacement was almost complete throughout. As the rock was rendered more compact in this process a shrinkage may have been the result, or the same volume may have been retained and the pores filled. That solution took place along with deposition seems to be shown by the almost complete destruction of the forms of organisms.

It is possible that the differences in the shales may be original, the result of variation in the material deposited. Whole series of beds of different material might have been deposited, giving rise to harder, more siliceous rocks than the soft varieties, and the same material might have been locally deposited in thin beds or in lenses and nodules, or have been intermingled with the others to form the intermediate varieties. But it would be difficult to say what this mate-

A. CHARACTERISTIC EXPOSURE OF FERNANDO GRAVEL.

Second ridge east of Figueroa Creek, 7 miles northeast of Los Olivos. Photograph by Ralph Arnold.

B. SHARP DOUBLE FOLD IN MONTEREY SHALE.

Looking east from point northwest of Zaca Lake; Zaca Peak in distance. Photograph by Ralph Arnold.

rial might have been, and the more or less completely crystalline character of the harder shales shows that metamorphism has taken place. The most plausible theory, therefore, is that the Monterey shale as originally laid down was fairly constant in character and that it has undergone alteration extensively, as well as very locally, through the agency of siliceous waters, the older portions of the formation, and possibly the more disturbed portions, having been most generally subjected to the change. The limestone has in places been altered after a fashion somewhat similar to that of the siliceous shales, being changed to marble, probably as the result of solution and redeposition.

The Monterey rocks likewise show the result of contact metamorphism to a very local extent in the vicinity of the diabase intrusions. The process seems to have been largely one of consolidation through baking. A limestone specimen obtained near the diabase intrusion north of Zaca Peak, in the San Rafael Mountains, gives an excellent illustration of shearing. The calcite crystals have all been arranged parallel and greatly elongated, so as to give the rock a schistose structure.

STRUCTURE AND THICKNESS.

The Monterey has nowhere been left undisturbed. In places it has been but gently folded. Pls. IV (p. 36), VIII, *B* (p. 78), and IX (p. 80) show examples of moderate tilting. But at other places, as at that pictured in Pl. VI, *B* (p. 46), it has been thrown into folds so sharp and closely spaced that the succession of the beds and thickness of the series are difficult to make out. The details of its structure are discussed under the heading "Structure" (pp. 76–78). The thickness of the whole series is at least 5,200 feet. Each of the two divisions comprises a maximum known thickness of 2,600 feet. No single complete section of the whole could be obtained.

EVIDENCE OF AGE.

A paucity of recognizable molluscan fossils is one of the prominent characteristics of the Monterey in this region, as in most others in the Coast Ranges where it outcrops. Moreover, the other fossils that it contains are of little value in indicating its age. Its position in the geologic column is determined by the lower Miocene fossils found just below its base in the Vaqueros and by the upper Miocene fossils found at or near the base of the Fernando formation, which lies unconformably above it.

The following two species of mollusks occur in the Monterey diatomaceous shale on the road just above the Pinal Oil Company's office, southeast of Orcutt: *Arca* aff. *trilineata* Conrad, *Phacoides* aff. *acutilineatus* Conrad.

METAMORPHISM OF THE SHALE BY COMBUSTION.

At many different places in the Santa Maria district and elsewhere the oil-bearing shale has been burnt to a pink or deep brick-red color, or turned into a hard vesicular rock like scoriaceous lava, as shown in Pl. V, *B*, p. 36. This metamorphism is due to the combustion of the hydrocarbon content. Though the combustion is usually local in its effects, the number and wide distribution of the occurrences of burnt shale lend importance to the phenomenon. Such altered shale is of some value as indicating where the rock has been bituminous and where the conditions have favored the occurrence of seepages.

LOCALITIES WHERE THE SHALE IS AT PRESENT BURNING.

A number of localities have been observed at which combustion is at present or has been in recent years in progress within the Monterey shale. One of these is on the north side of Graciosa Ridge, south of the Santa Maria Valley, near the Rice ranch oil well No. 1. When this locality was visited by the writers early in the autumn of 1906, a fire was burning underground in the shale, causing a smoke of disagreeable odor to issue from the surface and making the ground hot over an area of many square yards. Oil was oozing up at various points near by, and the ground was heated in the neighborhood of all these seepages. The holes from which vapor issued were coated with delicate crystals of sulphur. At the point where the burning was actually going on and all about in the vicinity, for a distance of several hundred feet in some directions, the shale was altered to a bright-red color, or baked almost to the hardness of compact igneous rock, or rendered vesicular like lava.

There can be no doubt that this fire was supported by the bituminous material in the shale, and it was probably started by brush fires, though these had occurred a good many months before, as shown by the new growth of the bushes. It was said that there was a brush fire about January 1, 1906, which started the fire in the shale, and that futile attempts to put it out by dumping dirt to smother it had been made ever since that time. It seems likely, however, that this same fire has been in progress for several years. This likelihood is borne out by other accounts. It is stated that sometimes during the course of brush fires on the hills sudden darts of flames may be seen at night from a considerable distance—the result of the setting on fire of gas escaping from the rocks.

Other cases of burning in the shale have been observed in recent years at the San Marcos ranch in the Santa Ynez Valley, and at the mouth of Rincon Creek, on the coast near Santa Barbara, as described by H. C. Ford.[a] The phenomena exhibited resemble those

[a] Bull. Santa Barbara Soc. Nat. Hist., vol. 1, No. 2, October, 1890.

of solfataras and have given rise to the opinion that volcanic activity is present in this region. This so-called "Rincon volcano" existed before 1855, being referred to in the Pacific Railroad reports; this shows that the burning has continued a long time.

TYPICAL OCCURRENCES OF BURNT SHALE.

Outcrops of burnt shale occur in eight or ten localities in the Santa Maria district. The best examples are at various places along the ridge of the Casmalia Hills from a point south of Schumann to Waldorf; on the north and south sides of Graciosa Ridge; and on Redrock Mountain 4 miles southeast of Los Alamos. In each of these regions every stage of alteration is exhibited, from the slightly discolored shale to hard slaglike rocks of varying shades of red and black. The area of altered shale in the different localities ranges from about a hundred square feet to a half a square mile or more, as at Redrock Mountain. In each the burnt rock is surrounded by unaltered, usually soft, white, diatomaceous shales which in most places show the planes of stratification. At no point observed was a sign of stratification left in the baked shale. In every occurrence the shales in the neighborhood are bituminous and asphalt deposits are usually adjacent.

The largest area of altered shale is on the summit and surrounding ridges of Redrock Mountain. This is the highest of the hills in the basin region between the San Rafael and Santa Ynez mountains, being 1,968 feet above the sea; the height of most of the summits in the vicinity is from 1,000 to 1,500 feet. Redrock Mountain seems to owe its prominence, at least in part, to the metamorphosed shale that forms its summit. Likewise, in the 800-foot hill on the southeast side of Schumann Pass, the capping of this same character, resembling volcanic rock, seems to have caused the topographic relief. The metamorphism in these localities probably took place a long time ago. At Redrock Mountain great deposits of asphalt are in places in contact with the altered shale, and there is a large area of shale impregnated with bitumen.

DEPTH TO WHICH ALTERATION HAS EXTENDED.

The depth to which alteration has extended below the surface in these occurrences is difficult to determine. A cliff of burnt shale 50 to 100 feet high is exposed 4½ miles due south of Guadalupe, and the difference of elevation of points in the Redrock Mountain neighborhood where the altered rock outcrops amounts to several hundred feet. That such metamorphism of the shale has not been solely a surface phenomenon is shown by the fact that burnt shale has been found at considerable depths in drilling. Mr. Orcutt, of the Union Oil Company, exhibited samples of red shale, coming from depths of 950

to 1,040 feet below the surface in Hill well No. 1, in the Lompoc field, which are identical in appearance and texture with the burnt shale elsewhere. Traces of petroleum were associated with the upper stratum of burnt shale in this well. In numerous other wells in the Santa Maria field red shale, doubtless burnt, was found at depths ranging between 90 and 330 feet below the surface. The hardening consequent on the burning has in some places rendered the rock difficult to pierce with the drill.

LITHOLOGIC CHARACTER OF BURNT SHALE.

The burnt shale exhibits all stages of change from a slight induration and discoloration, due, probably, to oxidation of iron, to an extreme hardening and partial fusion. Where slightly altered, the normal white shale assumes a light-pink color. From this stage it passes through various shades of rose and brick-red and deepens in color to a reddish, bluish, or greenish black, or even a true black. In the advanced stages of change it becomes a rough, brittle, reddish, porous slag, like vesicular lava, or a very hard, compact, dark, and dull-colored rock, looking something like a compact igneous rock. An example of partly vesicular and partly compact burnt shale is shown in Pl. V, *B* (p. 36). Burnt shale is not crystalline, but the texture is so variable as to give a patchy appearance to surfaces. In one place it may be compact and black, nearly full of irregular cavities, surrounded by patches of different colors; in another, vesicular and reddish. Whereas the weight of the original shale is slight, the lighter varieties having a specific gravity less than that of water, the excessively burnt shale is very heavy. The material has evidently contracted to much less than its original volume, the angular cavities and irregular vesicles being one consequence of this contraction.

Under the microscope the rock in the more advanced stages of alteration appears to have an exceedingly fine grained, amorphous, porous groundmass, discolored with reddish-brown or gray stains. Black filaments and dots appearing like carbonaceous material are common. Exceedingly minute rounded and irregular grains scattered through the whole, but forming no appreciable proportion of it, are the only portions visible under crossed nicols. They extinguish four times in a revolution of the field and are probably clastic quartz grains. These are characteristic of the unaltered shale as well.

G. H. Eldridge[a] notes an occurrence of burnt shale near the old Blake asphalt mine, south of Graciosa Ridge. He says: "The shale now appears red, ashlike to hard and clinker-like, glazed, or silicified; bodies of bitumen contained within this have the appearance of a coke, as though derived from the solid fixed carbon of the petroleum."

[a] The asphalt and bituminous rock deposits of the United States: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 1, 1901, p. 428.

The likeness of varieties of the burnt shale to volcanic rocks is indicated by the fact that Thomas Antisell, in his account of the geology of the Coast Ranges in the Pacific Railroad reports,[a] describes "scoriaceous" and "amygdaloidal lava," "whitish-gray, hard trachytic rock," "volcanic," and "igneous rocks" in the region of Santa Ynez River, evidently having reference to the burnt shale. He considered these rocks to be eruptive masses, forming the oldest and axial rocks of the hill ranges, whereas they are part of the Monterey shale, which overlies the basement formation. He regarded the associated diatomaceous shales in some places, although not in others, as "magnesian" and "tremolite" rocks of igneous origin, and refers to the places where the shale is burning as examples of present volcanic activity.

CAUSE OF THE ALTERATION.

There can be little doubt that the burnt condition of the shale is in all places the result of heat produced by combustion of its hydrocarbon content. The phenomenon is confined to the Monterey shale, which is the source of a large part of the California petroleum, and to those regions in which this formation is extremely bituminous. The shale in many such places is impregnated with petroleum and the cracks partially filled with it. The areas of altered shale are almost invariably situated in the vicinity of oil seepages, which usually denote a fractured condition of the rocks such as would allow fire to spread and be supported. The observance of fires actually in progress in the shale and the changes that have taken place in the neighboring rocks—changes in every way similar to those in localities where no fire exists at present—give the best clues to the manner in which the shale has been baked in other places. It is difficult to conceive another source of heat sufficient to cause local baking of the shale in otherwise unaltered strata at a depth of 1,000 feet below the surface in such a case as has been mentioned. Probably there, as on the surface, it was due to ignition of bituminous material. It is probable that fire started in the petroliferous shale at the surface and threaded its way downward along cracks partially filled with bitumen. The failure to smother the fire in the shale on Graciosa Ridge, previously noted, indicates that such fires are able to survive with a small air supply. On the other hand, if the above theory is correct, it indicates that a considerable amount of oxygen may be present in the rocks at such a depth.

In this connection it may be mentioned that the temperature in a well near the one in which the burnt shale was found was 152° F., at a depth of 3,600 feet. The cause of ignition may be kindled fires, lightning, or the spontaneous combustion of the hydrocarbons or

[a] Explorations and surveys for the Pacific Railroad, vol. 7, 1857, pp. 65–72.

surface vegetation. Many of the recent cases of burning are directly traceable to the first cause, but for those which may have taken place before the advent of man either the second or third cause will have to be invoked.

RANGE IN TIME OF THE PHENOMENON.

As already mentioned, the marked influence of the hardened shale on the topography in certain places indicates that it originated in those places a long time ago. The age of some of the burnt shale is further shown by the presence of numerous fragments of it at a depth of at least 10 feet below the surface in horizontal beds of Pleistocene age. These beds consist of sand, clay, and rough gravel, and form the low hills between Guadalupe Lake and the high hills to the west. The fragments of shale are little worn and evidently of local derivation, having possibly come from the cliffs already mentioned south of Guadalupe. The fact that the Monterey shale has undergone this kind of baking in Pleistocene as well as in recent time indicates further that the accumulation of the oil and its dissemination in the surface rocks took place, or were taking place, before the latest orogenic movements in this coastal region.

FERNANDO FORMATION (MIOCENE-PLIOCENE-PLEISTOCENE).

GENERAL STATEMENT.

The name Fernando was first applied by Homer Hamlin to a series of rocks overlying the Monterey in the San Fernando Valley, Los Angeles County. The formation has since been recognized by Eldridge and Arnold[a] in the region of the Puente Hills, Los Angeles, and Santa Clara Valley oil districts, where it is a series of unaltered sedimentary rocks lying unconformably over the Monterey, and probably representing a portion of upper Miocene time, the whole of the Pliocene, and a part of the Pleistocene. Its lower portion is the equivalent of the Santa Margarita and Pismo formations, and its upper portion is contemporaneous with the Paso Robles formation, as these three are described by Fairbanks in the San Luis folio.[b]

In the region at present under discussion the name Fernando is applied to a similar formation that represents a large part of the Pliocene and probably includes the upper Miocene and part of the lowest Pleistocene. It consists throughout of a series of sandstone, conglomerate, and shale resting unconformably upon the Monterey. Unconformities also exist locally within the Fernando. It attains a thickness of at least 3,000 feet, but no one section exposes the whole series and it is probable that the formation includes a considerably greater thickness. It is widespread in the northern part of Santa

[a] The Santa Clara Valley, Los Angeles, and Puente Hills oil districts, southern California: Bull. S. Geol. Survey No. 309, 1907, pp. 22-28.

[b] logic Atlas U. S., folio 101, U. S. Geol. Survey, 1904.

Barbara County, where it was deposited in the old basin between the Santa Ynez and San Rafael ranges. It covers up the Monterey over the greater part of the basin, and as its structure in most places there conforms approximately to that of the Monterey, it is a fairly good key to the folding that has taken place in this underlying formation. The relation between the Monterey and Fernando is of a somewhat perplexing nature. An unconformity in dip between the two was not to be definitely made out on examination of the exposed contact in any part of the central basin, because of the fact that the Monterey and Fernando were subjected practically to the same movements over a large part of the region. Lithologic similarity of parts of the Fernando to the Monterey is also an obstacle to their differentiation. But pebbles of Monterey shale and flint, showing here and there pholas borings and giving evidence of marine deposition, are abundant in the Fernando. In fact, the greater part of the coarse detrital material of the Fernando conglomerate is derived from the Monterey, proving that its period of deposition was one of erosion in the previously deposited shale, that it followed the uplift above sea level of a portion of the Monterey, and that it was subsequent to the formation of the flint in that shale series. The importance of the break between the two is indicated by the change in character of the deposits from organic, probably deep-water sediments almost free from erosional débris to sandy and gravelly deposits derived from the wearing away of hard land areas. This change was hardly as marked as that occurring in the reverse order at the close of Vaqueros time, although it accompanied what was probably a greater time and structural break. The apparent structural conformity between the Monterey and Fernando at most places within the basin region is probably due to the previously almost undisturbed attitude of the shale upon which the Fernando was laid down and the subsequent disturbance of both formations at the same time. But remnants of the Fernando left around the border exhibit less conformity with the underlying Monterey, owing doubtless to the fact that the shale of the latter was upheaved around the edges of the basin to form the mountains bordering it during the period intervening between the close of Monterey time and the beginning of deposition of the Fernando.

The chief importance of the Fernando in connection with studies of this oil field is derived from the facts that it hides the oil-bearing formation over a wide area; that it affords through its structure, however, a clue to the structure of the underlying Monterey; and that it acts as a reservoir for oil (Arroyo Grande field) and as a receptacle for escaping bituminous material. In the last-mentioned way it gives origin to asphalt deposits of economic value and to cappings of hard asphalt that may be of significance as an aid in the retention of the oil within the Monterey.

LITHOLOGIC CHARACTER.

This formation is mapped as a unit, although it certainly represents a long period during which sedimentation, continuous in the region as a whole, was locally intermittent and carried on under differing conditions, owing to the differential elevations to which the region was subjected. The stratum resting upon the Monterey in one place is apt to be absent in another, where an overlap of one or another stratum may occur. The lowest recognized Fernando rocks occur south of Sisquoc, where the Monterey is overlain by a bed of brecciated and waterworn shale derived from it and cemented by argillaceous sand, above which lies about 200 feet of fine sand, succeeded by a 50-foot layer of diatomaceous shale that is indistinguishable from that of the Monterey. Above this shale the series grades up through about 600 feet of fine white and yellow sand and coarse sand, until a bed of conglomerate is reached. At other places, as south of Waldorf and south of Harris, the lowest stratum found at Sisquoc is either wanting or of minor importance, and beds of diatomaceous shale lie conformably over the Monterey shale, making the dividing line very hard to find. West of Waldorf the contact is marked for miles by a bed of brecciated Monterey shale of coarse and fine fragments, in places cemented into a hard amalgam by a paste of bituminous material. Here the overlying beds are made up of fine shale and sand and pebbly sandstone, which, though actually separated by an important unconformity from the Monterey, as indicated by the brecciated zone and the abundance of pebbles of that formation in them, are conformable in dip with the underlying beds. A still younger series of fossiliferous shale and sand marks the base of the Fernando 1½ miles northeast of Divide, and also northeast of Schumann and northwest of Mount Solomon; and on the summit of the ridge in the vicinity of the head of Pine Canyon, halfway between the two latter localities, the Monterey is capped by what appears to be a part of the same series somewhat younger still. This shows that at the locality near the head of Pine Canyon either an overlap of the late Fernando occurred on an old eminence of Monterey shale that was above the sea at the time of the deposition of the part of the Fernando immediately preceding, causing the omission on its summit of hundreds of feet of sediments which were deposited around its base; or else the portion of the Fernando preceding this series was removed from above the Monterey during a period of erosion within Fernando time, this period being followed by subsidence.

Along the ridge 1 mile southeast of Redrock Mountain, in the Purisima Hills, there is a capping of diatomaceous shale resembling that of the Monterey in every respect, but containing characteristic Fernando fossils. It was not suspected that this shale belonged to a formation distinct from the Monterey until the fossils were found.

It would be difficult to work out the limits of the area that this remnant covers. In all probability it is very small, and it has not been shown on the map. This shale here forms the base of the Fernando. A pebbly layer with constituent well-worn pebbles of Monterey shale embedded in sand has aided in the accumulation of asphalt on the summit of the ridge near by, where it probably marks the basal line of the Fernando formation.

Above the soft diatomaceous or gritty shale and fine white sand that is common at or near the bottom of the Fernando the bulk of the formation is composed of rather loosely consolidated fine white and yellow sand and coarser gray sand that grades here and there into thick beds of loose conglomerate. The conglomerate is made of well-worn pebbles, mostly of flint and hard shale, embedded in a coarse sandy matrix. Locally the sand and conglomerate are extremely hard, owing usually to the presence of a large number of mollusk shells from which a calcareous cement has been derived. The most prominent bed of conglomerate, and one that seems to be constant over the whole region, occurs from 800 to 1,000 feet up in the series (above the lowest horizon) just north of Canada de los Alisos, on La Laguna grant. What is probably the same bed is well exposed in cliffs west of Canada Laguna Seca, 1½ miles south of the Los Alamos Valley. This loose aggregate of sand and pebbles in alternating strata of coarse and fine material is dominantly composed of the light-colored pebbles of Monterey shale. Pebbles of other varieties occur more sparingly. Above the conglomerate lies a stratum of limestone that is constant over the whole region and seems to mark a division in the Fernando. There are two or more massive beds of hard limestone interbedded with soft, gray, very alkaline, earthy material, making a total thickness ranging from 10 to perhaps 50 feet. Its fossils indicate that it is of fresh-water origin, and possibly it marks the base of a fresh or brackish water series. The portion of the Fernando overlying this limestone probably corresponds to the fresh-water Paso Robles formation of the Salinas Valley described by Fairbanks in the San Luis folio. In some places where this higher portion of the Fernando above the limestone has not been worn away, it is found to consist of little-consolidated beds of fine sand, gravel, and clay that look as if they might have been laid down in fresh water, but no proof of their origin has been found. Such beds are well exposed in the foothills of the San Rafael Range north of Santa Ynez, where they weather characteristically into cliffs at the summit of hills. A view of such an exposure is given in Pl. VI, *A* (p. 46), which affords a good idea of the rough alternating beds of coarse material. No good lithologic or paleontologic criteria are known by which this series may be separated from the lower portion of the Fernando, and they are therefore mapped as a unit.

STRUCTURE.

As has been stated, the Fernando is generally so nearly conformable with the Monterey that it is difficult to draw a line between them on the basis of a discrepancy in dip. Nevertheless, it is in general true that folding has been gentler in the Fernando than in the Monterey. It would seem that the older formation had been disturbed in varying amounts, in some places severely and in others gently, during the process of uplift that put an end to its period of deposition. As a result the dips at the present time in the Fernando are apt to be less steep than in the Monterey, but folding has gone on largely along old lines, so that conformity in strike between the two formations is the rule.

Wide, low folds are characteristic of the structure in the Fernando within the Santa Maria basin region. This is illustrated by the broad anticlines in this formation in the Solomon Hills, the broad anticline in the Purisima Hills, and the synclines in the Los Alamos and Santa Rita valleys, in which the dips range from 5° to 25° as a rule for a long way on either side of the fold and rarely become steeper than 30° or 35°. In places, as south and west of Sisquoc and west of Canada Laguna Seca, the beds are almost if not quite horizontal, but this is exceptional. Curves and plunges in the preexisting low folds in the Monterey gave rise to structural basins in which the Fernando was deposited as a filling. Such was the origin of the oval area of Fernando sand covering the eastern portion of the Todos Santos y San Antonio grant. This basin is the westward extension of a great synclinal basin that runs from that locality first eastward and then southeastward across the Los Alamos, La Laguna, and Corral de Quati grants and has determined the position of the Los Alamos Valley. The northern arm of this syncline slopes gradually up to the axis of the Solomon Hills, and the southern arm rises abruptly into the Purisima Hills, the slope on both sides conforming with the topography. The region of low slopes covered by parts of the Mission La Purisima and Santa Rita grants is a somewhat similar wide synclinal basin filled with soft Fernando sediments. The Fernando is steeply upturned along the northeastern border of the Casmalia Hills, where it stands almost vertically in contact with much disturbed and in places overturned beds of the Monterey shale. It is upturned also where it rests against the serpentine north of Alamo Pintado Creek on the La Laguna grant, and southwest of Los Alamos it seems to dip very steeply under the brow of an overturn in the Monterey. In the San Rafael Mountains patches of Fernando deposits occur as remnants, and the beds in many places are steeply folded or turned completely on edge. They exhibit unconformity with the Monterey. In at least three places the Fernando is affected by faulting—a few miles west of Los Alamos, in the neighborhood of Cebada Canyon, and along the fault

crossing Labrea Creek. In the first two the dip of the beds is moderate and the disturbance is not great.

DISTRIBUTION.

An idea of the distribution of the Fernando may be well obtained from the map (Pl. I, in pocket), as it is not covered by so many formations as the older series. It is much more widespread near the surface, however, than appears on the map, since it is probably present and hidden by only thin deposits over a great part of the area mapped as terrace deposits and alluvium.

The general character of the Fernando is that of a filling. Its soft, loose, spreading sands, which preserve poorly evidence of low folds, form moundlike hills and broad valleys that convey the idea of a filled topography. But, on the other hand, harder beds and surface cappings due to hardening by iron oxide, which not uncommonly produce sharp, square outlines, are marked features of the topography, as in the vicinity of Mount Solomon, at the head of Howard Canyon. On the northeastern border of the Casmalia Hills, between Schumann and Graciosa Canyon, a lime-hardened sandstone predominates and forms a prominent ridge. In the Santa Rita Hills the lines of structure that there curve around from a westerly direction to the southeast are brought out by the resistant limestone which supports the northeast flanks of the hills. The wide-stretching foothills of the San Rafael Range north of Santa Ynez have a character all their own. They are formed of gravel, clay, and sand that have the appearance of belonging to a fresh or brackish water series, and they stand out with many bold faces that have been cut in the soft formation, as illustrated in Pl. VI, *A*. Elsewhere the dominant character of the Fernando and its topographic forms are due to the soft sand which forms the major portion of the series.

EVIDENCE OF AGE.

At least five and probably six distinct horizons are recognizable in the Fernando by means of characteristic fossil faunas. The localities at which these different faunas occur, named in their probable relative order, beginning with the oldest, are as follows:

(*a*) South of Waldorf in soft shale; south and east of Sisquoc in fine sandstone.

(*b*) "Sea-urchin bed," Squires (Santa Maria Oil and Gas) lease; California Coast lease; south of Graciosa-Western Union wells; west of Harris Canyon; vicinity of Hill wells in the Lompoc field; and near head of Howard Canyon.

(*c*) Waldorf asphalt mine, railroad cut 1 mile northeast of Schumann; Pennsylvania asphalt mine at east end of Graciosa Ridge; all in gray shale or fine gray sandstone.

(*d*) Waldorf asphalt mine; railroad cut 1 mile northeast of Schumann; Fugler Point asphalt mine; Sisquoc (or Alcatraz) asphalt mine; and points along north flank of Casmalia Hills, in coarse sandstone or conglomerate.

(*e*) East end of Folsom lease in soft sandstone.

(*f*) Fresh or brackish water beds immediately west of the mouth of Canada Laguna Seca.

The beds at horizon *a* are of marine origin, are probably upper Miocene in age, and correspond in a general way to Fairbanks's Santa Margarita and Pismo formations. Those at horizons *b*, *c*, *d*, and *e* are of marine origin, are closely related, belong at the base of the Pliocene, and are in a general way the equivalents of the middle Purisima and lower and upper San Diego formations. At horizon *f* are beds of fresh-water origin, probably representing Fairbanks's Paso Robles formation and Lawson's marine Merced formation.

The following is a list of the fossils obtained from the Fernando:

Fernando (upper Miocene-Pliocene-Pleistocene) fossils from the Santa Maria district, California.

	4469	4471	4472	4473	4474	4475	4476	4477	4481	4485	4486	4487	4488	4489	4490	4491	4492	4506	4523
Actæon sp																×			
Amphissa (?) sp				×															
Angulus sp				×															
Arca sp. a				×															
Arca sp. indet										×				×					
Arca trilineata Conrad (Pl. XXIV, fig. 5)		×	×	×	×	×						×						×	×
Astyris richthofeni Gabb (Pl. XXIV, fig. 3)				×	×		×		×										
Balanus cf. concavus Bronn					×		×												
Bathytoma carpenteriana Gabb var. fernandoana Arnold (Pl. XXIII, fig. 7)							×												
Bathytoma cf. tryoniana Gabb				×															
Bittium arnoldi Bartsch				×															
Bittium casmaliaensis Bartsch				×															
Cadulus fusiformis Sharp and Pilsbry (Pl. XXI, fig. 8)				×															
Calliostoma sp. indet				×	×														
Callista subdiaphana Carpenter			×	×		×							×						×
Cancellaria sp. a			×	×		×													
Cancellaria crawfordiana Dall var. fugleri Arnold (Pl. XXI, fig. 9)						×													
Cardium meekianum Gabb					×	×										×			
Cardium sp. indet		×																	
Chione sp																×			
Chlorostoma (?) sp		×																	
Chrysodomus sp							×												
Clidiophora punctata Carpenter (Pl. XXIII, figs. 2, 3)							×												
Crepidula princeps Conrad (Pl. XXIV, figs. 1, 2)		×		×		×				×			×			×		×	×
Crucibulum spinosum Sowerby					×														
Cryptomya ovalis Conrad (Pl. XXII, fig. 7)		×				×			×	×				×					
Cumingia californica Conrad (Pl. XXIII, fig. 5)						×													
Dosinia ponderosa Gray (Pl. XXII, fig. 8)		×				×				×					×				
Drillia graciosana Arnold (Pl. XXI, fig. 18)			×																
Drillia johnsoni Arnold (Pl. XXI, fig. 13)				×															
Drillia waldorfensis Arnold (Pl. XXI, fig. 12)				×															
Echinarachnius ashleyi Merriam (Pl. XXIV, figs. 6, 7)	×								×		×	×							
Echinarachnius cf. excentricus Eschscholtz var. (Pl. XXIV, fig. 8)					×											×			
Fusus sp. a		×	×																
Fusus sp. b										×									×
Galerus inornatus Gabb						×				×									
Glycymeris cf. barbarensis Conrad					×	×				×									
Kennerlia (?) sp			×	×															
Leda orcutti Arnold (Pl. XXII, fig. 9)			×	×	×								×						
Leda taphria Dall (Pl. XXII, figs. 3a, 3b)				×															
Lucapina cf. crenulata Sowerby						×													
Lunatia lewisii Gould (Pl. XXI, fig. 3)		×		×	×	×													

***Fernando* (*upper Miocene-Pliocene-Pleistocene*) *fossils from the Santa Maria district, California*—Continued.**

	4469	4471	4472	4473	4474	4475	4476	4477	4481	4485	4486	4487	4488	4489	4490	4491	4492	4506	4523
Lymnæa alamosensis Arnold (Pl. XXI, figs. 6, 7) [a]																			
Macoma nasuta Conrad (Pl. XXII, fig. 5)		×		×	×		×			×									×
Macoma sp				×															
Macoma cf. secta Conrad					×														
Mactra sp						×	×			×									
Miopleiona oregonensis Dall				×		×													
Modiolus rectus Conrad				×	×	×				×									
Monia macroschisma Deshayes					×														
Muricidea sp					×														
Mya truncata Linné				×															
Mytilus sp. indet					×														
Nassa californiana Conrad (Pl. XXIV, fig. 4)		×			×	×	×	×	×	×									
Nassa waldorfensis Arnold (Pl. XXI, fig. 17)				×	×														
Natica clausa Broderip and Sowerby (Pl. XXI, fig. 16)				×	×	×													
Neverita reluziana Petit (Pl. XXI, figs. 14a, 14b, 15)					×	×	×												
Ocinebra lurida Middendorf					×														
Ocinebra micheli Ford var. waldorfensis Arnold (Pl. XXI, fig. 10)				×															
Olivella biplicata Sowerby					×		×												
Olivella cf. intorta Carpenter									×										
Opalia anomala Stearns				×	×														
Opalia varicostata Stearns				×	×														
Ostrea veatchii Gabb (Pl. XXIII, fig. 10)				×	×														
Ostrea possibly veatchii Gabb			×																
Panomya cf. ampla Dall						×													
Panopea generosa Gould		×		×	×	×													
Pecten (Plagioctenium) near cerrosensis Gabb						×													
Pecten (Patinopecten) healeyi Arnold (Pl. XXVI, figs. 1, 2)					×							×							
Pecten (Pecten) hemphilli Dall (Pl. XXV, fig. 5)					×														
Pecten (Chlamys) lawsoni Arnold (Pl. XXV, fig. 3)					×	×													
Pecten (Patinopecten) oweni Arnold (Pl. XXV, figs. 2a, 2b)										×									
Pecten (Pecten) stearnsii Dall (Pl. XXV, figs. 1a, 1b)						×													
Pecten (Chlamys) wattsi Arnold (Pl. XXV, fig. 4)						×													
Phacoides annulatus Reeve (Pl. XXIII, fig. 8)																			
Phacoides intensus Dall (Pl. XXIII, figs. 9a, 9b)				×	×														
Phacoides nuttallii Conrad var. antecedens Arnold (Pl. XXII, fig. 6)		×					×												
Pholadidea ovoidea Conrad (Pl. XXII, figs. 1a, 1b)						×													
Pholadidea (?) sp. indet																			
Platyodon cancellatus Conrad var					×														
Pleurotoma (Borsonia) sp. a																			
Pleurotoma sp. b						×													
Priene oregonensis Redfield var. angelensis Arnold (?)																			
Priene oregonensis Redfield (Young) (Pl. XXI, fig. 2)																			
Purpura crispata Chemnitz (Pl. XXII, fig. 2)																			
Saxidomus gracilis Gould					×														
Saxidomus (?) sp. a																			
Scala sp. a																			
Sigaretus debilis Gould		×																	
Siliqua cf. edentula Gabb		×																	
Solen cf. sicarius Gould				×	×	×	×												
Spisula catilliformis Conrad var. alcatrazensis Arnold (Pl. XXIII, fig. 6)		×																	
Spisula sisquocensis Arnold (Pl. XXIII, fig. 1)		×																	

[a] Fresh-water beds in the Fernando formation, 1 mile southeast of bench mark 425, Los Alamos Valley.

Fernando (upper Miocene-Pliocene-Pleistocene) fossils from the Santa Maria district, California—Continued.

	4469	4471	4472	4473	4474	4475	4476	4477	4481	4485	4486	4487	4488	4489	4490	4491	4492	4506	4523
Tapes cf. lacineata Carpenter		×			×		×												
Tapes staleyi Gabb		×			×					×									×
Tapes tenerrima Carpenter (Pl. XXII, fig. 10)		×				×	×	×											
Tellina sp.		×		×															
Tellina aff. bodegensis Hinds													×						
Terebratalia occidentalis Dall (Pl. XXII, figs. 4a, 4b)						×													
Thalotia caffea Gabb (Pl. XXI, figs. 4, 5)						×													
Thracia cf. trapezoides Conrad						×													
Thyasira aff. gouldii Philippi				×															
Tresus nuttallii Conrad					×											×			
Tritonium sp. indet				×															
Trochita radians Lamarck (Pl. XXI, fig. 1)						×													
Trochita sp. indet																		×	
Turritella cooperi Carpenter (Pl. XXI fig. 11)			×	×	×														
Venericardia californica Dall (Pl. XXIII, fig. 4)			×	×	×	×													

4469. One hundred yards northeast of California Coast oil well No. 3, 1 mile east of Divide, and 3 miles southeast of Orcutt.
4471. Alcatraz asphalt mine, 3 miles east of Sisquoc.
4472. Pennsylvania asphalt mine, 3½ miles southeast of Orcutt.
4473. Waldorf asphalt mine, 3 miles south-southeast of Guadalupe.
4474. Railroad cut 1 mile north of Schumann station.
4475. Fugler Point asphalt mine, 1 mile north-northeast of Gary, at head of Santa Maria Valley.
4476. Asphaltum layer above Monterey shale, near Folsom well No. 3, Santa Maria oil field, 3 miles southeast of Orcutt.
4477. Near Folsom well No. 4, Santa Maria oil field, 2½ miles southeast of Orcutt.
4481. Five miles N. 30° E. of Lompoc bench mark 95, in prominent sandstone beds around Purisma oil wells.
4485. One-half mile south of Sisquoc.
4486. *Echinarachnius ashleyi* horizon, immediately west of Santa Maria Oil and Gas Company's well No. 4, 2 miles southeast of Orcutt.
4487. Immediately east of head of Howard Canyon, 4 miles north-northeast of Los Alamos. *Echinarachnius ashleyi* horizon.
4488. On ridge south of road about 2½ miles northwest of Blake.
4489. Southeast side of La Zaca Creek, where it empties from steep canyon; at base of asphalt sandstone in shale, 8 miles north of Los Olivos.
4490. Four miles east-northeast of Los Alamos, on Cuaslui Creek.
4491. Gully 2½ miles west-northwest of Blake.
4492. One and three-fourths miles S. 5° W. of bench mark 425 of Los Alamos Valley, one-half mile northwest of sink on top of ridge.
4506. One mile southeast of summit of Redrock Mountain, along ridge, near 1,700-foot knob.
4523. One mile due south of Sisquoc, in ravine.

QUATERNARY.

GENERAL STATEMENT.

Three distinct classes of Quaternary deposits younger than the latest Fernando can be differentiated in this region, although it is difficult to distinguish between them areally. They are terrace deposits, dune sand, and alluvium, each one of which as mapped may possibly represent more than one period of deposition. They are deposits of comparatively little thickness laid down unconformably upon the older formations subsequent to the greater part of the disturbance and deformation that has affected the region.

TERRACE DEPOSITS.

GENERAL DESCRIPTION.

Terraces are common in this region and are among the most prominent topographic features. They are fairly even surfaces, invariably

inclined slightly toward the ocean or the line of drainage, and ranging in size from tens of square miles to only a few feet square. The more extended terraces fringe the coast line and the larger valleys and cover areas of low hills. The smaller ones are scattered over ridges and hilltops and along the smaller valleys. These terraces are covered with a thin coating of sand and gravel, and here and there with clayey material. The distribution of the deposits is well shown on the map, with two general exceptions. In the first place, many of the strips of land along valleys mapped as covered with terrace deposits may not represent true terraces, as it is almost impossible to draw definite distinctions between such horizontally bedded valley fillings, true terrace cappings, and recent alluvium. All post-Fernando deposits in small valleys are therefore mapped with the terrace formation, and alluvium is shown only in the extended valley bottoms, where dividing lines between it and the terrace deposits are drawn arbitrarily. In the second place, owing to the lithologic similarity of the Fernando and the terrace-deposit sand and the similar surface appearance of these two formations, the attempt has been made to represent on the map only a few areas of the terrace sand overlying the Fernando. The Fernando is doubtless capped by terrace deposits in many places, but it is usually impossible to tell whether this is true or not. The lines of contact between these formations are of necessity arbitrarily shown.

This similarity causes much difficulty in places in determining whether the deposits belong to the Fernando or to the later epoch, and whether it is necessary to go through a great thickness of Fernando beds or only a few feet to reach the Monterey below. Where fossils, distinct lines of bedding, or tilted strata are present they are indications that the sand belongs to the Fernando.

The terraces are found commonly at all altitudes up to 1,200 feet, and a few even as high as 1,400 feet. None have been definitely recognized at a higher elevation.

LITHOLOGIC CHARACTER.

The material of the terrace deposits is usually sand and conglomerate, for the most part the former. The sand is medium grained and contains scattering waterworn pebbles. It is normally soft and grayish, but in many places compact, being stained a reddish yellow and hardened by iron oxide or filled with iron-stained concretions. In this surficially compacted state it forms hard cappings on hilltops and slopes. Round, bullet-like, iron-hardened concretions are characteristic of the derived soil. Over much of the surface of Burton Mesa and in other places this deposit occurs as loose, grayish sand, hardened locally by the action of rain water and various salts or oxide of iron. The conglomerate—or gravel, as it might equally well

be called—is composed of bowlders, pebbles, and fragments of Monterey flint and shale, besides pebbles of other rocks in smaller quantity. Some of the pebbles are very much waterworn, but in places the number of unworn fragments of shale almost necessitates the use of the word "breccia" in describing the deposits. Evidence of bedding is rarely prominent in the typical terrace deposits, but they invariably appear to lie horizontal, seeming to have been little disturbed by the uplift of the land that brought them to their present elevation.

No fossils have been found in these deposits, but they contain numerous pholas-bored pebbles of Monterey shale, and in places, as on Burton Mesa, the Monterey shale itself, upon which the deposits lie, has been bored by these marine mollusks.

Many of the cappings formed parallel with the surface through hardening by iron oxide have the appearance of being beds with appreciable dip, and are therefore misleading. The thickness of the coating of Burton Mesa is 25 or 30 feet and the cover of the typical terrace in other parts of the region has about the same thickness. Whether it attains a much greater development than this at any place is hard to tell. These shallow coverings hide considerable areas of the Monterey and obscure its structure, but most of the canyons that cut into the terraces reveal the presence of the oil-bearing formation beneath. The thickness of the coatings is not sufficient to make a serious difference in the depth to which it is necessary to drill for oil. The deposits are economically of importance as reservoirs for the oil escaping from the Monterey shale, and thus they give rise to accumulations of asphalt. It is usually impossible to tell whether the sand that helps to form the asphalt is a terrace deposit or belongs to the Fernando. The terrace sand can not form as deep asphalt deposits as those due to the Fernando sand.

In some of the valley fillings above mentioned, as for instance along Salsipuedes Creek, and at the west edge of the Santa Maria Valley between Guadalupe Lake and the Casmalia Hills, there occur horizontally bedded deposits of clay, sand, and gravel differing in appearance from the terrace deposits and possibly differing in age and origin. A good example of an old valley filling which now forms the summit of a hill is shown in Pl. IV, *B* (p. 36). It consists of a sandy and earthy material through which rock fragments and pebbles are scattered. It illustrates the usual unconformity of the post-Fernando deposits with the older formations. The low hills in the region of Santa Ynez are formed largely of horizontal beds of fine gravel unlike the Pleistocene deposits found elsewhere. These exhibit in one place an appearance of being tilted, though this may be due to cross-bedding.

ORIGIN.

Most of the terrace deposits are probably of marine origin. This is proved in the case of the most typical deposits by the presence of the pholas borings already mentioned. The deposition was carried on in shallow water and much of the material was derived on the spot from the wearing away of the shore line of Monterey shale, the fragments of which were not always subjected to much polishing before being deposited and protected from agencies of erosion. These deposits give undeniable evidence of a great uplift of the coast during Pleistocene time. It seems most probable that the terraced surfaces resulted from marine planation along gradually rising shore lines and that the formation covering them represents the beach and shore deposits. The rise of the land was probably too rapid and the amount of sediment too small to allow much off-shore extension of the deposition. The material that may have been deposited in the deeper places determined by the depressions in the topography has since probably been largely removed by erosion. The terrace deposits themselves have been extensively eroded and in many places are left as mere remnants. Some of them have no doubt been subsequently added to by wind-blown sand.

It is probable that some of the terraces and horizontal Pleistocene deposits along valleys have been formed by streams. Most of the valley fillings were probably laid down in this way. At the mouths of some canyons, as along the western side of Graciosa Canyon, Pleistocene deposits have been built up in the shape of detrital fans, which have since been carved into flat-topped, steep-sided blocks by recent streams.

DUNE SAND.

The prevailing northwesterly wind from the ocean has amassed great deposits of sand in places along the coast. The process has probably been going on all through the Quaternary period and it is hard to distinguish the older of the eolian deposits from those partially or entirely of marine deposition. The line of contact of these formations as mapped is arbitrary.

The greatest mass of dune sand occurs at the northwest end of the Casmalia Hills, where the gradual slope down to the sea from an elevation of about 1,200 feet is covered by loose, yellow sand of probable eolian origin. This drifts about incessantly and is probably still in the process of collecting, being supplied from the long, low, open shore to the north and held in check by the bulwark of the Casmalia Hills on the south. This deposit has a thickness of several hundred feet. At its base along the coast is exposed a basal layer of large bowlders and horizontally stratified sand. The original slope of the

hills was probably at least partly covered during the uplift of the coast by marine terrace deposits similar to those found elsewhere in the region, these being later buried by the gathering wind-blown sand. Recent marine shells are widely scattered over the surface of this sand, but are not considered by the writers as indicating its marine origin. They were probably carried there by Indians or birds.

South of the Casmalia Hills, where the coast is open to the winds, sand dunes are continually forming and covering up the terrace deposits. The sand is not retarded by an inland barrier, however, as on the north of the hills, and no such vast deposit has been formed. The sand is continually being carried into the interior valleys and spread thinly over a wide area.

ALLUVIUM.

All the valleys of this region contain a certain amount of alluvial material and stream gravels, which reach in many localities a thickness of 50 feet or more. In some places the deposit is earthy, in others sandy earth, and in still others pure sand, gravel, or clay. It is as a rule horizontally stratified. Recent deposits of this character attain considerable extent in the wide valleys, but it is not easy to distinguish them from Quaternary deposits of different age or of somewhat different origin. They are mapped as distinct only in the larger valleys and the contact lines are arbitrary. Practically all the hills and valleys within the territory mapped have a covering of soil.

IGNEOUS ROCKS.

GENERAL STATEMENT.

The formations in this region are chiefly of sedimentary origin, but eruptive and intrusive igneous rocks of various ages appear. These are all basic in composition. Layers of volcanic ash high in silica interbedded with the Monterey are discussed with the sedimentary series (p. 37). The center for igneous rocks is in the region around Point Sal of which Fairbanks made a special study, and the statements here made in regard to the igneous rocks of that region are based largely on his description.[a]

IGNEOUS ROCKS OF PRE-MONTEREY AGE.

Fairbanks describes a small intrusion of basalt having a laccolithic appearance in the Knoxville (lower Cretaceous) shales north of Mount Lospe, in the Casmalia Hills, and a large neighboring area of spheroidal basalt that he is certain is older than the Monterey

[a] Fairbanks, H. W., The geology of Point Sal: Bull. Dept. Geology, Univ. California, vol. 3, 1896, pp. 1-92.

and believes to antedate the Knoxville. It is closely associated and intermingled with bodies of diabase and gabbro. This complex forms Point Sal Ridge and the rocky headland of Point Sal. Another complex that he believes belongs in the Knoxville forms a long dike north of Schumann Canyon. It is an exceedingly complicated intrusive mass of gabbro and peridotite that has been penetrated by later dikes of diabase, norite, gabbro, and intermediate types of rock.

The areas mapped as Franciscan (Jurassic) are largely occupied by serpentine that was originally intruded in Franciscan strata. This serpentine may be older than the Knoxville, and the last-mentioned occurrence of gabbro and peridotite may be contemporaneous with it.

Diabase was struck at a depth of 1,300 feet in the Pezzoni well No. 1, southwest of Sisquoc. It is a considerably altered rock composed largely of serpentine and plagioclase feldspar, with some augite, possibly a small amount of unaltered olivine, considerable magnetite, and several accessory minerals. This occurrence is of considerable importance as affecting the prospects for the production of oil in this neighborhood. The question arises whether this diabase has intruded the Monterey, as in the San Rafael Mountains, or whether it is a part of the older igneous formations, in which diabase is common. The fact that the rock is so much altered probably indicates that it belongs to a formerly exposed older formation upon which a fairly high portion of the Monterey shale series has overlapped. It is hardly conceivable that an intrusion at such a depth in the shale could have undergone so much alteration. In either case, whether this diabase marks the base of the Monterey or whether the shales have been intruded by an igneous mass, the conditions are unfavorable for the discovery of oil in the immediate vicinity.

IGNEOUS ROCKS INTRUDING THE MONTEREY.

The youngest igneous rocks occurring in the Santa Maria quadrangle and those of chief interest in the present connection are intrusive in the Monterey (middle Miocene). Such are five small areas of diabase mapped by Fairbanks south of Point Sal and two areas of diabase in the San Rafael Mountains. The age of the two latter is somewhat in doubt, but the metamorphic and disturbed appearance of the Monterey shale in their vicinity indicates that they originated as dikes intruding the Monterey. The shale appears hardened and baked in the immediate neighborhood and narrow tongues of Monterey shale, certainly altered along the contact, extend into the mass on Tepusquet Creek. Along its edges appear patches of *Aucella*-bearing sandstone belonging to the Knoxville, which were probably brought up from below by the intrusion. The diabase in both areas is of dark-green color and coarse texture and exhibits sheared serpentinous facies.

Another intrusion of probable post-Monterey age forms a single outcrop in the hills 7 miles northeast of Point Conception. It is a dike of basic porphyry related to basalt. On one side of the outcrop the bases of horizontally lying rough pentagonal columns are well exposed. It is not known whether the sedimentary rocks through which this is intruded belong to the Monterey or the upper part of the Vaqueros.

GEOLOGIC HISTORY.

EARLIEST PERIODS.

The general geologic aspect of the Santa Maria district is that of a region of comparatively recent geologic formations. Tertiary rocks, in places covered by Pleistocene deposits, are predominant, those of Cretaceous and Jurassic age less widespread, and older formations entirely absent. The Tertiary has received almost all the attention in the present study and little can be said of the history of the region previous to that period. The much-disturbed and metamorphosed Jurassic sediments (Franciscan), intruded by serpentine, form the basement of the whole region, but outcrop only very locally. In Cretaceous time a considerable thickness of marine sediments was laid down, but these deposits were probably not greatly disturbed before the beginning of deposition in the Tertiary. To the present time they have remained unmetamorphosed and no more affected by mountain-making forces than later formations. Igneous intrusions, however, took place at different times in the Cretaceous.

EOCENE PERIOD.

All the greater divisions of the Tertiary, with the possible exception of the Oligocene, are represented by marine sediments, the major part of this time having been taken up by sedimentation. The relations between the Cretaceous and Eocene rocks have not been studied. Sedimentation began at some time in the Eocene not yet determined, in the southern portion of the region mapped, and continued nearly to the end of the Eocene, when it ceased for a period of unknown length. It was probably in the period just preceding that of the deposition of the Eocene sediments that the forces began to work which caused the structural features south of the region where the San Rafael Mountains now stand to assume an east-west trend. In this way may have been formed the depression extending east and west across the region now occupied by the Coast Ranges, which afforded a basin of deposition for the Eocene and possibly a connection between the ocean and the basins in which strata of the same age were deposited in the interior. A large part of the Santa Ynez Mountains is composed of Eocene strata which have been lifted up along east-west lines of structure. The main

uplift did not occur at the close of Eocene time, but it is probable that orogenic movements did bring to a close the period during which the Eocene sediments were laid down by raising the strata slightly above the sea and preventing for a time further deposition. How long this time was is not known, but it corresponds approximately with the Oligocene.

LOWER MIOCENE PERIOD.

The movements immediately following the deposition of the Eocene caused no appreciable disturbance in the Eocene strata, and when sedimentation recommenced over the same area in lower Miocene time neither the old nor the new strata preserved any positive evidence in their relative position that a time break had occurred. The great masses of coarse conglomerate forming the base of the lower Miocene portion of the group record a change to conditions of very shallow water, and the abrupt change of faunas indicates that a long time interval separated their deposition from that of the subjacent Eocene. It is most probable, however, that the post-Eocene movements, which were gentle, were also somewhat local, and that in portions of the Santa Ynez Mountains to the east of the region under discussion sedimentation was more nearly continuous. At about the close of the Oligocene period the Eocene basin was again depressed; deposition of sediments, almost entirely of detrital origin and very similar to those previously laid down, ensued in a widening area covered by the sea; and subsidence of the land gradually continued. The Vaqueros formation, which resulted from this period of depression, represents the greater part of lower Miocene time.

MIDDLE MIOCENE PERIOD.

The middle Miocene (Monterey) shale formation is one of striking individuality, and conditions of unusual character prevailed during its period of deposition. At the beginning of middle Miocene time the land sank over a large part of the region of California now occupied by the Coast Ranges and fairly deep water conditions became prevalent. The wearing away of extended land areas ceased as they became submerged, and the material for the formation of coarse detrital deposits was no longer plentiful. Two varieties of deposits, which were largely of organic origin, were the chief ones to be formed during the long period that followed. These were the laminated limestones and the much more abundant siliceous shales. Silt of extremely fine grain, both of siliceous and argillaceous nature, was swept into the sea waters, probably from considerable distances, and settled down to form a considerable proportion of the deposits; but sand and other coarse detritus found their way only at rare intervals

to the main portions of the quiet sea bottom which was formerly the surface of the land and which had been given a comparatively low relief by the long period of erosion that preceded the submergence.

During the period of transition between the Vaqueros and the Monterey, limestone was formed chiefly, but somewhat inclosed basins where deposits of alkaline mud were laid down apparently existed in places. Such a basin is indicated by the alkaline gypsiferous clays on the south side of the Casmalia Hills, probably representing upper Vaqueros. In some places, as, for instance, in the San Rafael Mountains, sandstone beds were formed early in Monterey time, probably in the neighborhood of locally unsubmerged areas. But later very little sand was deposited anywhere. Further submergence no doubt took place during the period, removing the sources of this sand and allowing to be deposited under fairly constant conditions a thickness of beds greater than a mile. It is not probable, however, that the depth of the sea was at any time as much as this, being more likely closer to half a mile.

During the early part of Monterey time conditions were variable, calcareous and siliceous deposits alternating, probably as a result of alternating temporary predominance in the sea of organisms with calcareous or siliceous shells. As the period progressed the siliceous organisms became more predominant and remained so, making up a large fraction of the total bulk of the Monterey formation. It was an age of diatoms. These small marine plants lived in extreme abundance in the sea and fell in showers with their siliceous tests to add to the accumulating ooze of the ocean bottom, just as they are forming ooze at the present day in some oceanic waters. It is well known that diatoms multiply with extreme rapidity. It has been calculated that starting with a single individual the offspring may number 1,000,000 within a month. One can conceive that under very favorable life conditions, such as must have existed, the diatom frustules may have accumulated rapidly at the sea bottom and aided the fine siliceous and argillaceous sediments in the quick building up of the thick deposits of middle Miocene time. A principal obstacle to the rapid accumulation of the diatoms might be the limited supply of silica from which these algæ derive the material of their tests. Other organisms with their shells and skeletons were also present to aid in building up the shale beds. They were Radiolaria and Foraminifera; sponges with their spicules, which were abundant; Crustacea; fishes, the remains of which are numerous in the shales; and mollusks with delicate shells, which are common, though poorly preserved.

Volcanic eruptions, possibly submarine, broke out at different times during the latter part of the lower Miocene (Vaqueros) and the early part of the middle Miocene (Monterey.) They may have accompanied movements that took place during the transition

period. Acidic volcanic ash of a rhyolitic type was ejected, and it settled in the ocean to form regular beds of considerable thickness and extent interstratified with the other sediments. The occurrence of ash interbedded with diatomaceous earth that probably belongs fairly high in the Monterey formation indicates that these eruptions did not cease in the early part of middle Miocene time. Neither the centers of eruptions nor any lava equivalents of the ash have been found in the field. Similar eruptions were characteristic of the lower and middle Miocene for long distances north and south of this region.

LATE TERTIARY AND EARLY QUATERNARY PERIOD.

The Monterey period of deposition was brought to a close by orogenic movements which folded the shales and lifted them above the sea in many places. In some regions the folding was intense, the greatest disturbances accompanying the uplift of the mountain ranges to an altitude of thousands of feet. The San Rafael Mountains, which were upheaved at this time, probably extended along the lines of former mountains, and some smaller mountainous or hilly areas likewise, such as the Casmalia Hills and perhaps portions of the Santa Ynez Range, followed former zones of uplift. But for the most part the Santa Ynez Range was probably new. It is doubtful whether it was ever completely covered by Monterey sediments, and its structure may have been determined by minor folding previous to the beginning of the Monterey, but it is probable that this range did not have any approach to its present proportions until after middle Miocene time. In other regions low, broad folds were formed during the post-Monterey disturbance and the strata were not upheaved to a great altitude; such was the case in parts of the basin region between the San Rafael and Santa Ynez mountains.

After the formation of the middle Miocene shales they were intruded at several different points by basic igneous masses, mostly of the nature of diabase. The disturbance which put an end to the period was profound and this igneous activity was probably an accompaniment of it. The rocks were locally hardened by contact action in consequence of the intrusions.

After an erosion interval, probably of comparatively short duration, the land again sank, though not so extensively nor to such depth as in the previous subsidence, and a large part of the Santa Maria district, especially the lower regions, became submerged. The deposition of the Fernando followed, beginning before the close of the Miocene. Owing to differences in altitude and possibly also to local difference in the amount of subsidence, the deposition began in some places before it did in others. Over the areas in which the Monterey has been only slightly folded, the Fernando beds assumed conformable positions with it. In regions where the Monterey beds

had been more highly tilted the later sediments were laid down unconformably. In places the first Fernando beds were of similar lithologic character to the Monterey shale, being deposited probably under similar conditions or else derived from the redeposition of the shale material. This similarity, added to the bedding conformity, caused the formations to appear as completely conformable and continuous. But the presence in places of layers of brecciated Monterey shale at the base of the Fernando, and in places of true angular unconformities, proves that a period of erosion preceded the Fernando deposition.

After the period of deposition of the finer sediments usually found at the base of the Fernando, shallow-water conditions prevailed. The deposits were almost entirely detrital, the product of erosion on land, much of the material coming from areas of Monterey shale. Fresh-water or possibly brackish-water conditions may have prevailed in the latter part of Fernando time. They certainly did for a time and locally, at least, when the brackish-water limestone beds were formed.

MAIN QUATERNARY PERIOD.

Downward and upward movements of the coastal region were probably in progress during the Fernando period, but were intensified early in Pleistocene time, and disturbance of the strata along the lines influenced by the post-Monterey upheaval took place. In this way the mountain ranges were upraised in their present position and the Fernando became warped along the lines of further folding in the Monterey.

After this uplift erosion set in and eventually removed the Fernando from some parts of the region over which it had formed a thick covering. The mountain regions were worn into rugged shapes, Santa Maria and Santa Ynez rivers developed graded valleys, and the sea planed off the coast extensively by cutting. During the same period, however, land building over this region was in progress as the result of differential movements of the coast. The great resultant changes of level in post-Fernando time, as indicated by the records, were a pretty general depression to a depth of 1,100 to 1,200 feet, and locally to at least 1,400 feet; and a later uplift to the present level. These movements were probably gradual and continuous, but not sufficiently slow to allow the formation of deposits of great thickness. During these movements the sea cut into the land as the water encroached and receded, forming terraces inclined toward the ocean, and beach and shallow-water sediments were laid down as thin coatings over the newly planed surfaces. These deposits were probably formed as the land rose. During the periods of depression the streams built up deposits of gravel, sand, and clay at different levels, giving rise to extensive terraces and to filled valleys. Great deposits

of wind-blown sand were formed also, and their formation is continuing at present. During the late Quaternary the deposits and topographic forms resulting from all these processes have been carved by erosion; wide areas have been denuded of the thin Pleistocene capping; and in many places bits of terrace deposits are left merely as scattering remnants.

STRUCTURE AND CONDITIONS AFFECTING THE PRESENCE OF OIL.

THE ANTICLINAL THEORY.

The anticlinal theory of oil accumulation assumes that the oil, being of lesser gravity, rises above the water present in porous rocks and collects at the highest possible points in upward folds, being there confined by impervious strata arching over the folds. The presence of water, according to this theory, is considered as fundamentally necessary for the carrying out of the process of accumulation in anticlines.

The presence of oil in anticlinal folds was repeatedly observed in the eastern part of North America during the latter half of the nineteenth century. E. B. Andrews noted its occurrence along low anticlines in West Virginia and Ohio as early as 1861, and described this occurrence that same year,[a] and again, with more assurance of its wide application, in 1866.[b]

In 1863 the Canadian geologists,[c] in describing the oil springs immediately north of Lake Erie, noted their close relation to the anticlinal structure, and formulated the theory that the rise of the oil is due to the presence of water in the rocks. Their brief statement is as follows:

> Some of these springs appear to be on the line of the great anticlinal which runs through the western peninsula, and subordinate undulations of a similar character will be found connected with others. The oil, being lighter than water and permeating with it the strata, naturally runs to the highest part, which is the crown of the anticlinal, whence it escapes to the surface by some of those breaks which are usually found in such positions.

Also in 1863 Sterry Hunt, to whom the above-cited conclusions in the Canadian report are probably due, described the oil of western Ontario as derived from low anticlines.[d]

The following quotation is from an account written in 1885 by I. C. White[e] of his search for some method of determining the location of gas accumulations:

> In the prosecution of this work I was aided by a suggestion from Mr. William A. Earsenian, of Allegheny, Pa., an oil operator of many years' experience, who had

[a] Am. Jour. Sci., 2d ser., vol. 32, July, 1861, pp. 85-93.
[b] Am. Jour. Sci., 2d ser., vol. 42, July 1866, pp. 33-37.
[c] Geology of Canada, Canadian Geol. Survey, 1863, p. 379.
[d] Am. Jour. Sci., 2d ser., vol. 35, March, 1863, pp. 169-170.
[e] Science, vol. 5, No. 125, June 26, 1885.

noticed that the principal gas wells then known in western Pennsylvania were situated close to where anticlinal axes were drawn on the geological maps. From this he inferred there must be some connection between the gas wells and the anticlines. After visiting all the great gas wells that had been struck in western Pennsylvania and West Virginia, and carefully examining the geological surroundings of each, I found that every one of them was situated either directly on or near the crown of an anticlinal axis, while wells that had been bored in the syncline on either side furnished little or no gas, but in many cases large quantities of salt water. Further observation showed that the gas wells were confined to a narrow belt, only one-fourth to 1 mile wide, along the crests of the anticlinal folds. These facts seemed to connect gas territory unmistakably with the disturbance in the rocks caused by their upheaval into arches, but the crucial test was yet to be made in the actual location of good gas territory on this theory. During the last two years I have submitted it to all manner of tests, both in locating and condemning gas territory, and the general result has been to confirm the anticlinal theory beyond a reasonable doubt.

The anticlinal theory was found applicable, according to Redwood,[a] by various investigators in the Eastern Hemisphere, in the Caucasian and Carpathian fields, in India, Persia, and Algiers, and as stated by Lyman,[b] in some at least of the wells in Japan. Further credence has been lent to it by investigators in various parts of the world in subsequent reports on oil districts. It has, however, not been proved to be of universal application.

ACCUMULATION OF OIL IN THE SANTA MARIA DISTRICT.

In the Santa Maria and Lompoc fields the evidence indicates that anticlinal structure is favorable although probably not absolutely essential to the accumulation of oil. But whether or not this fact is explainable on the basis of the anticlinal theory as previously advanced, and as seemingly applicable to eastern fields, remains a question, for the reason that definite evidence is lacking regarding the presence or absence of water in the strata containing the oil. The fields of the Santa Maria district are not yet old enough to make it ascertainable whether water occupies lower levels in the same porous strata in which the oil is contained, or strata below those containing the oil, and whether water will take the place of the oil on its exhaustion in the wells; or, on the other hand, whether the oil occurs unassociated with water in large amounts. What evidence there is throws doubt on the assumption that water is present in sufficient amounts materially to affect the position of the oil in the strata. Although over a hundred wells have been sunk to depths ranging between 1,500 and considerably more than 4,000 feet in various positions relative to the axes of folds, water has been reported in only four wells at a depth of more than 1,000 feet below the surface, or below sea level, and in only a few wells below 300 or 400 feet. In other words, whatever water is present occurs in all but four wells

[a] Redwood, Boverton, assisted by Holloway, G. T.: Petroleum and its products, London, 1st ed., 1896, vol. 1, pp. 44-46; also 2d ed., 1906, vol. 1, p. 112.

[b] Geological survey of the oil lands of Japan, Tokio, 1877 and 1878.

near the surface, or at least considerably above the oil-producing zones.

It may be questioned whether the presence of water is essential for the accumulation of petroleum in the upward folds of the strata under the conditions presented by the Santa Maria and Lompoc fields. Here the oil tends to rise to the surface and form seepages wherever channels of escape are offered. This is probably not due to hydrostatic pressure, as there is no evidence that the water tended to rise in the same way; and it is just the opposite of the tendency ascribed to oil by upholders of the anticlinal theory, which would result in the oil descending and gathering in the synclinal troughs on subsidence or removal of the water. In the fields under discussion the oil is always intimately associated with gas. There do not seem to be, as a rule, separated stores of gas and oil, but the two are intermingled, or at least closely brought together, so that one is not usually found without the other, although gas is sometimes found alone. The oil exhibits a tendency to migrate, as shown by its original concentration from widely separated points of origin, by its surface seepage, and by the energetic way in which it rises in the drill holes when a source of it is tapped. This migratory faculty may be ascribed entirely to the presence of the associated gas, which would cause the oil to fill every crevice offering a point of escape or a point of lodgment. If this is granted, it is evident that the points of accumulation of oil will be determined chiefly by the presence of cavities, large or small, offering a place for it to gather. Anticlines, being points of fracturing and in some places opening out of the strata, would afford likely places for the oil to lodge in those beds subject to fracture and for it to be imprisoned by overarching impervious beds.

Aside from ideas as to accumulation of oil after such a fashion, the writers have come to the conclusion that in this region many of the "oil sands," so called, are not true sands, but zones of fractured shale or flint offering interspaces in which the oil can gather. Beds of sand in the Monterey are scarce and thin. Some of the oil-producing zones are very thick, amounting to tens or even hundreds of feet. The oil occurs chiefly in the lower portion of the formation, where brittle, flinty shale is abundant; and as it is a noticeable fact that wherever these hard, flinty layers appear at the surface they are usually much more contorted and fractured than the associated softer shales, which are, in general, only folded and not broken, it seems likely that the same fracturing and resultant formation of an ideal reservoir for the oil takes place in the depths as at the surface. Where it is so fractured, the shale occupies a greater volume than before, showing spaces some of which are open and others partially or wholly filled with chalcedonic or bituminous material. The unfractured beds are more or less impervious to the rapid migration of the petroleum, and so act as barriers to keep the oil in the porous zones.

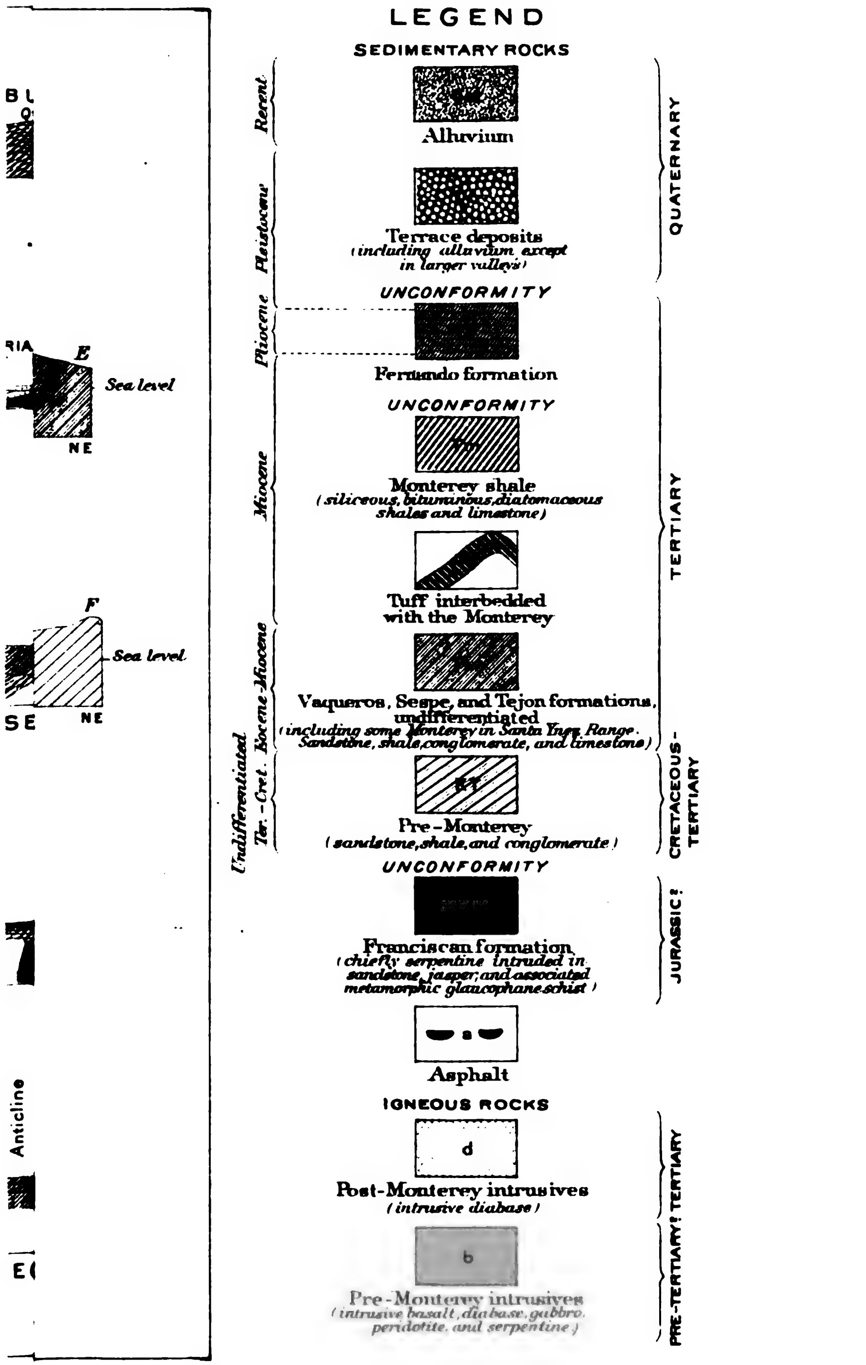
It is therefore possible that in the Santa Maria district the gas pressure is the chief agent in giving the oil mobility, and that the condition of the rocks is the chief factor that controls the matter of where the oil is stored most abundantly. Hydrostatic pressure may not play an important part. The especially large accumulations in anticlines may be accounted for primarily by the cavities offered by the strata along upward folds, and secondarily by the presence of less pervious beds arching over such folds and affording favorable conditions for the confinement of oil and gas tending to escape. Lesser stores of oil may occur at other points within the formation.

INDICATIONS OF OIL.

The chief criteria for judging as to the presence or absence of oil in appreciable quantities in this region have been the attitude of the beds, their position in the series, and the surface indications. Other minor evidences of a local nature have also been taken into account. In drawing conclusions from structural indications anticlines have been considered as the chief factors favoring accumulation, inasmuch as the oil appears to have gathered in them in a majority of the proved occurrences in this district, other conditions being favorable. The conclusion has been reached that anticlines afford a fairly trustworthy clew to the location of the most important oil deposits. Close folding appears to play a part in this district in depriving the rocks of their oil, and excessive disturbance and fracturing is unfavorable to its retention. But, on the other hand, moderate folding would appear to be favorable, if not requisite, for the accumulation of stores of oil, and probably the most favorable conditions are afforded by anticlinal folds of such sharpness as to render the brittle rocks porous by fracturing, but to leave less pervious arches of more elastic rock.

The second criterion is the statigraphic position in the formation of the beds exposed over the area in which oil is sought. As has been before stated, the oil-bearing strata occur chiefly in the lower portion of the Monterey. Where the outcropping beds belong to the higher portion of the formation there is a greater likelihood that the underlying oil-bearing strata have been able to retain their contents than where the lower strata have been denuded of the greater part of the overlying beds or where they are themselves exposed or partially removed.

As regards the third criterion, the chief surface indications are afforded by the presence of seepages of oil or tarry material from the shales, by asphalt deposits, bituminous shales, and burnt shale. Asphalt occurs mainly in three ways—as a mixture of bituminous material with sand, due to the absorption by overlying sand deposits of seepages from the shale, as hardened fillings of asphalt in cavities along joints, and as excessively saturated shale. The burnt shale is


LEGEND
SEDIMENTARY ROCKS
Recent
Alluvium
Pleistocene
Terrace deposits
(including alluvium except in larger valleys)
QUATERNARY
UNCONFORMITY
Pliocene
Fernando formation
UNCONFORMITY
Miocene
Monterey shale
(siliceous, bituminous, diatomaceous shales and limestone)
Tuff interbedded with the Monterey
TERTIARY
Eocene-Miocene
Vaqueros, Sespe, and Tejon formations, undifferentiated
(including some Monterey in Santa Ynez Range. Sandstone, shale, conglomerate, and limestone)
Ter.-Cret.
Undifferentiated
Pre-Monterey
(sandstone, shale, and conglomerate)
CRETACEOUS-TERTIARY
UNCONFORMITY
Franciscan formation
(chiefly serpentine intruded in sandstone, jasper; and associated metamorphic glaucophane schist)
JURASSIC?
Asphalt
IGNEOUS ROCKS
d
Post-Monterey intrusives
(intrusive diabase)
TERTIARY
b
Pre-Monterey intrusives
(intrusive basalt, diabase, gabbro, peridotite, and serpentine)
PRE-TERTIARY? TERTIARY
E
Sea level
NE
F
Sea level
SE
NE
Anticline

the rose-colored or slaglike rock observed at many places in this and other oil-bearing regions within the Monterey formation. It is fully discussed on pages 48–52. It is the result of the burning of the hydrocarbons that have impregnated the shale, and its presence therefore indicates where seepages have existed.

GENERAL STRUCTURAL CONSIDERATIONS.

The area comprised within the limits of the Lompoc and Guadalupe quadrangles has been subjected to two systems of forces acting obliquely to each other, the one producing structural features which trend northwest and southeast, the other those which trend east and west. (See Pl. VII.) The system causing the northeast-southwest structure was probably the older and dominating one, as it brought forth the highest ranges and most extreme folding and conformed with the great system which has determined not only the Coast Ranges of California but the western border of the North American continent. The forces producing the east-west features, although exceedingly effective from the west end of the Santa Ynez Range eastward to the region south of the end of the San Joaquin Valley, were not so far-reaching as those of the other system and probably began to exert themselves at a later date.

That portion of the area under discussion which lies to the northeast of the Santa Maria Valley is dominated almost completely by structural lines trending northwest and southeast; in the extreme southern portion lines trending east and west prevail. The region between these two areas is occupied by folds and faults, some of whose component parts exhibit allegiance to one system and some to the other, but whose resultant trend is intermediate between the two. In a general way the lines of disturbance as well as the topographic relief within this central province radiate fanlike from the point of divergence of the Santa Ynez and San Rafael ranges east of the town of Santa Ynez.

The forces acting throughout the region have more often found equilibrium in the production of folds than in adjustment by faulting. Several important faults are recognizable, however, and doubtless others will be revealed by detailed work, especially in the San Rafael Range. There is evidence to show that forces have acted intermittently along the same general lines throughout a long period of time.

DETAILED DISCUSSION OF STRUCTURE.

In the field study of the structures of the formations and in the present discussion special attention has been paid to the structure of the Monterey shales, because that formation has apparently given origin to the petroleum and in it the bulk of the oil is stored.

For convenience the two quadrangles will be divided into the three naturally separated portions outlined in a preceding paragraph, viz, the region of the San Rafael Range, which includes all of the territory northeast of the Santa Maria Valley and a line extending southeast of its head; the region of the Santa Ynez Range; and the province of low hills and shallow valleys intervening between the two mountain masses. The reading of the following paragraphs describing the structure of various areas should be accompanied by reference to the map. (Pl. I, in pocket.) For the sake of compactness the conclusions as to the possibilities of productiveness of the Monterey shale have been stated, together with the description of its main structural features.

It must be remembered that in regions of great disturbance such as the shales have undergone in some parts of the area it is difficult to represent by single lines the complexity of the structure. Some of the lines, therefore, mark zones of folding rather than single definitely continuous folds. The dotted lines of structure are purely suppositional.

REGION OF THE SAN RAFAEL MOUNTAINS.

AREAS OF ROCKS OLDER THAN THE MONTEREY.

Whatever succession of beds or structural conditions may once have existed in the Franciscan formation (Jurassic?) in this district, they have been largely obliterated by the successive folding and crushing to which these rocks have been subjected in the long period of time since their first uplift. The shales and sandstones mapped as pre-Monterey, especially where the beds alternate, have preserved the folds well, but except on North Fork of Labrea Creek and along Sisquoc River no effort has been made to work out the structure of this series.

AREAS OF MONTEREY AND LATER FORMATIONS.

FOLDS.

Considered as a whole the Monterey has been thrown into a series of anticlinal and synclinal folds striking about N. 50° W., and apparently plunging, in the main, toward the northwest. Great variation exists in the relative steepness of dip along these folds, but it is evident that the compressive forces producing them were of much greater strength in the southeastern part of the area, between Bone Mountain and Round Corral Canyon and thence southeastward into the region of Zaca Peak. Here the folds become so compressed and in places overturned that it is difficult to trace them. Pl. III, *B* (p. 34) and VI, *B* (p. 46) give an idea of the closeness of the folding. In contrast with this constricted portion is the broad series of folds which extend

rather uniformly along the northeastern border of the area, and develop toward the southeast into the syncline crossing Tunnel Canyon and Horse Gulch just north of Sisquoc River. The high, broad ridge between Bone Mountain and Manzanita Mountain is composed of Monterey shale, which lies approximately flat, and toward the northwest becomes one arm of the great syncline which extends through Goodchild's ranch on Labrea Creek and is traceable almost to Colson Fork of Tepusquet Creek. A similar syncline, possibly the same, extends from Colson Fork northwestward across Tepusquet Creek to the margin of the Lompoc quadrangle. The northeastern arm of this fold forms the high ridge extending along the southwestern side of Buckhorn Canyon.

It is possible that the pre-Monterey rocks north of Bee Rock Canyon plunge down monoclinally under the Vaqueros in a fold at right angles to the wide anticlinal fold that exposes the former. Such a plunge would be apt to give rise to the northeast-southwest table between Bone Mountain and Manzanita Mountain that interrupts the structure to the northwest and southeast, and this table may, therefore, represent a buckling across an otherwise continuous structure.

Southwest of Los Coches Mountain one or more folds are overturned, but the northwestern extensions of these folds have not been examined.

The region southeast of Round Corral and Asphaltum creeks is occupied by several sharp folds which strike in a general northwest-southeast direction. Overturning is not uncommon in this series of folds, one notable example being an anticline on the southern flank of Zaca Peak. West of Round Corral Creek the structure lines bow around from a northwesterly to a westerly or west-southwesterly direction, the folds at the same time becoming less compressed and the conditions for the retention of the oil in the basal sands of the hard shale series correspondingly better.

FAULTS.

There is strong evidence of a fault zone passing north of the narrow area of intrusive rock north of Zaca Lake, and thence northwestward as far as the head of Rattlesnake Canyon. The resultant downthrow along this zone of displacement is on the southwest, probably amounting to a good many hundred feet toward the east edge of the Lompoc quadrangle. Toward the northwest this fault apparently dies out or merges into a syncline.

Just east of Los Coches Mountain there may be another fault which brings up the uppermost Vaqueros on the north. A third fault between the Pliocene and Monterey may extend from a point near the mouth of Round Corral Canyon to Labrea Creek.

Faults also occur along the Franciscan-Fernando contact in the region northwest and southeast of Figueroa Creek, but the resultant throw was not determined. A depositional contact is clearly exposed along this same line just northwest of Alamo Pintado Creek.

EVIDENCES OF PETROLEUM.

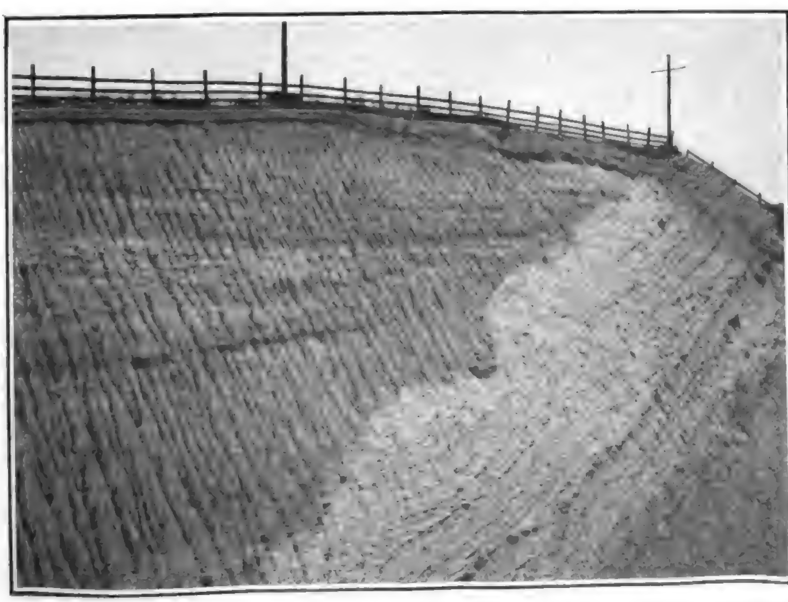
Despite the great development of folds within the Monterey area, only here and there do seepages of asphaltic material occur. It would seem that the fractures produced by sharp folding would give adequate channels for the escape of petroleum, and it is surprising to find so few seepages. The best developed of these is on Labrea Creek at and near its junction with Rattlesnake Canyon, and is typical of the localities noted north of Sisquoc River. The oil seepage is associated with small springs of strongly saline and sulphurous water, and the oil has exuded along the bedding planes of the Monterey shales, here thrown into a pronounced anticline which has been flexed in such a manner as to open out the laminæ of the shale and thus give better opportunity for the passage of oil. Two wells have been sunk here, but they are shallow and offer no additional data.

The following is a brief statement of the asphalt seepages and brea deposits occurring in the San Rafael Mountains:

1. Branch of upper Tepusquet Creek. Slight seepage in bed of creek three-fourths of a mile above junction with main stream. At anticlinal axis. Has been located.
2. On Colson Fork of Tepusquet Creek. Black bituminous streaks, veinlets, and pockets, associated with calcareous shales which are considerably folded on a minor scale. This also has been located.
3. Labrea Creek, at and near junction with Rattlesnake Canyon.
4. Sisquoc dairy. Seepage and asphaltic sands along sharply defined anticline which is obscured by later material. Well sunk here, but no record available.
5. Sisquoc River, one-half mile below Round Corral Canyon. Slight seepage from steeply inclined Monterey shale. (Shown in Pl. III, *B*, p. 34.)
6. Fugler Point, 1 mile north of Gary. Veins of asphaltum, parallel in a general way to the bedding, which here dips 25° SW., intrude the fossiliferous Fernando (lower Pliocene portion). A shaft has been sunk here a few feet for the removal of the asphaltum.
7. Alcatraz mine, 3½ miles east of Sisquoc post-office. Vast deposits of asphaltum, from a few feet to 200 feet or more in thickness, lie unconformably above the steeply dipping Monterey shales over large areas in the general region of the mine. These deposits have been mined on a large scale at one place, but at present the plant is idle. The mine is shown in Pl. VIII, *A*.
8. Zaca Canyon, 5 miles southeast of Sisquoc post-office. Deposits similar to those at the Alcatraz mine are found on both sides of La Zaca Creek where it debouches from its narrow mountain canyon into the broad valley carved by it through the hilly country.
9. Sisquoc Ridge, 1¾ miles north of Sisquoc post-office. A small but significant area similar in occurrence to the two preceding. This area overlies the axis of an anticline in the Monterey shale.

A. ALCATRAZ ASPHALT MINE, 3 MILES EAST OF SISQUOC.

Showing the horizontal Fernando brea deposits overlying the steeply tilted Monterey shale.



B. UNCONFORMITY BETWEEN TILTED MONTEREY SHALE AND HORIZONTAL PLEISTOCENE SAND AND GRAVEL.

In railroad cut northeast of Casmalia. Photograph by Ralph Arnold.

CONCLUSIONS REGARDING FUTURE DEVELOPMENT.

On account of the greater intensity of the folding and the lack of the thick, more or less unaltered diatomaceous deposits which are found associated with all the proved productive fields in this district, the indications are not so encouraging for good wells in the territory northeast of the head of the Santa Maria Valley as they are in certain other portions of the Lompoc and Guadalupe quadrangles. The areas in the region of the San Rafael Mountains which offer the most inducements for testing by the drill are as follows:

1. North and northwest of Sisquoc post-office, along the anticlines shown on the map (Pl. I, in pocket). There are one or two local anticlines not shown, which might also be prospected with good results. The hard shales exposed in this region are probably lower Monterey and, if such, do not offer as much promise of great accumulations of oil at their base as if they were overlain by the upper part of the formation. The strata in the region above the headwaters of Round Corral Canyon and Asphaltum Creek are too sharply folded to give much hope of the retention of large deposits of petroleum. The asphaltum deposits here and to the southeast indicate that the Miocene was at one time highly petroliferous, but that at least a considerable portion of the oil has escaped.

2. In the Monterey area bordering the head of the Santa Maria Valley on the northeast, both west and east of Tepusquet Creek, wherever the anticlines are not so sharply folded as to give indications of probable loss of their petroleum content by excessive fracturing. The surface evidence of petroleum in this general Monterey area is greatest in the southeastern or more sharply folded portion, but for obvious reasons it seems likely that the chances for the accumulation of economically important deposits of petroleum are greatest in the less compressed area northwest of Labrea Creek.

3. The region about Fugler Point and thence southward and southeastward toward Sisquoc. This territory is doubtless underlain by the oil-bearing beds, but at what depth it is not possible to calculate owing to the fact that the Monterey and Fernando are covered by later sediments. The occurrence of asphaltum at Fugler Point is analogous to that at the east end of Graciosa Ridge, near which very productive territory has been developed. The local dip at the point (25° SW.) would indicate that the best places to drill would be east of the asphaltum deposit; but the uncertainty whether this dip is anything more than a local tilting of the Fernando is so great that conclusions regarding the best localities for exploitation in this immediate vicinity are extremely hazardous. Southwest of Fugler Point, however, there is evidence of the presence of a low

anticline which should yield good returns if penetrated deep enough. This anticline is mentioned further in connection with the Canada del Gato[a] area (pp. 88–89).

REGION OF SANTA YNEZ MOUNTAINS.

AREA SOUTH OF LOMPOC.

South of the Lompoc Valley, the Monterey dips in general northward away from the higher portion of the hills, but south of the town of Lompoc is an area of much disturbance, and many folds have been developed on the flank of what may be thus broadly considered as a monocline. These folds have been compressed in different directions and there is a puzzling diversity of dip and strike. There are so many local folds that it is difficult to connect the more important axes, but the general lines of disturbance are continuous for the distance mapped. The main folds south of Lompoc are an anticline near the valley and a syncline north of the Monterey-Vaqueros contact, with a minor anticline and syncline between. The attitude of the beds is extremely variable, the dip ranging in general between 15° and 60°. On either side of the main anticline between Salsipuedes and San Miguelito creeks the hard shales dip away at an angle of 20° to 40°. West of San Miguelito Creek the folds swing out toward the valley or die out on the flank of the monocline, which thus becomes unbroken.

The greater part of the strata in the hills south of Lompoc belong low in the Monterey formation, although higher portions remain in the synclinal folds. The disturbance has been considerable, and erosion has removed the highest parts of the formation, so that the chances have been good for the escape of any oil that may have been present. There are no surface indications of petroleum and the conclusion is that no great quantity of oil would be found on drilling.

AREA OF SANTA RITA HILLS.

East of Lompoc the lines of structure cross the Santa Ynez Valley into the Santa Rita Hills. These hills are formed of a single main ridge which is paralleled on the south side by an important anticline. The dips on either side of the broad summit of this fold range from a few degrees to about 35°. The general trend of the fold is east and west, in conformity with that of the Santa Ynez Range, but it is curved, especially at the east end, as if influenced by more than one set of forces. Other important folds occur on the flanks of the anticline, giving origin to the disturbed zone followed by Santa Ynez River.

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[a] Called locally Cat Canyon.

A, B. MONOCLINE IN MONTER

About 1½ miles northwest of Casmalia, lookin

C, D. GRACIOSA AND WESTERN

South side of Santa Maria field; Mount Solom

NTEREY SHALE IN CASMALIA HILLS.

..ing northwest. Photograph by Ralph Arnold.

RN UNION OIL COMPANIES' WELLS.

..on in distance. Photograph by Ralph Arnold.

The conditions along this anticline, especially through the eastern half of its length, favor the occurrence of some oil at least, as the axis exposes beds fairly high in the formation and the folding is gentle. No surface indications of petroleum were found, except a patch of burnt shale south of the road about 1 mile southwest of the highest hill (elevation 1,300 feet) and local outcrops of bituminous black flint and brown shale on the west side of the 800-foot hill about half a mile north of the river and 1½ miles west of the east edge of the Santa Rosa grant.

MAIN PORTION OF THE SANTA YNEZ RANGE.

The Santa Ynez Range is composed chiefly of Tejon and Vaqueros rocks and its structure is therefore much less important in connection with the oil deposits than that of the areas underlain by the Monterey shale. It is dominated by a great southward-dipping monocline that forms a high ridge along the coast, north of which the strata are gently folded along curving lines that reflect two different structural trends. The folds that expose the Tejon-Vaqueros and the underlying Franciscan beneath the Monterey toward the west end of the range are in places abrupt and complex. The anticline of the Santa Rita Hills has the appearance of crossing the Santa Ynez Valley and continuing in a large fold to the southeast.

REGION BETWEEN THE SAN RAFAEL AND SANTA YNEZ MOUNTAINS.

CASMALIA HILLS AND SAN ANTONIO TERRACE.

Two dominant structural lines control the region of the Casmalia Hills and the San Antonio terrace. One is a typical fault starting on the coast south of Lions Head and the long area of igneous rocks and running southeastward. About 2 miles west of Casmalia the line is continued by an anticline, which is probably affected by faults at least as far as Schumann Canyon. This anticline plunges more and more toward the southeast and loses its character as a fold, giving place to the eastward-dipping monocline of the San Antonio terrace.

The other structure line is one of varying character, represented on the map as the Schumann anticline. Northeast of the area of igneous rocks that meets the sea at Lions Head Miocene strata form a great monocline, dipping rather steeply to the northeast. In the high region of Mount Lospe and northeast of the long strike ridges (shown in Pl. IX, *A*, *B*) that extend southeastward from that peak, this monocline flattens out into a structural platform of very low dip, which on approaching the edge of the steep descent to the Santa Maria Valley bends over and drops off abruptly. The axis along which this steepening of the dip occurs is in a way equivalent

to an anticlinal axis and is the line mapped. In places it is a true anticline, completed by beds of gentle dip that form a broad syncline of the platform on its southwest side. South of Corralillos Creek the structure curves westward and the Schumann anticline is sharply defined and overturned. It is seemingly to be correlated with a large anticline exposed in the Tejon-Vaqueros rocks on the coast north of Point Sal. South of Waldorf this anticline, as shown by the dotted line on the map, is not certainly continuous, but west and south of Schumann the same or a similar fold becomes well developed and the strata dip away from it on both sides. In this portion and southeast of Schumann Canyon its summit is broad, but the dips become very steep farther out on its northeastern flank. It plunges to the southeast and finally dies out.

Asphalt and other surface indications of oil, such as burnt shale and bituminous shale, occur at many places in the Casmalia Hills. The shale is especially bituminous along and near its contact with the Fernando on the northeastern side of that part of the hills which lies north of Schumann, and it has been burnt in a number of places in the same region. Outcrops of burnt shale are prominent on the hill just southeast of Schumann, and near the contact at the northern base of this hill the shale is extremely bituminous. Wells put down in the region about Schumann encounter heavy tar at depths below 2,000 feet, but no paying wells have been struck. It seems likely, however, that at greater depths, possibly 3,000 feet or so, the horizon of the productive flinty beds encountered in the Graciosa Ridge wells will be penetrated and will yield lighter oil in paying quantities.

The region lying north of Schumann Canyon, west of the valley that runs southward out of the hills and opens to Schumann Canyon 1 mile N. 45° W. of the Casmalia depot, and west of the road that crosses the ridge to Waldorf will probably not yield any large quantity of petroleum, because the strata are so low in the formation and because there appear to be no sufficiently well-developed folds to afford good points of accumulation. Oil might be found in small quantities in the minor folds between the lower portion of Schumann Canyon and the fault. The shale along the coast here is very bituminous. East and south of the supposedly unproductive region outlined above the plunging structure exposes higher portions of the Monterey shale and the conditions warrant the conclusion that oil can probably be obtained in the neighborhood of the major anticline. Southeast of the point where the road south of Waldorf crosses the ridge the territory appears promising, especially along the anticline and on its east side. The oil which is supposed to rise on the steep eastern flank of the fold probably does not reach far under the broad western flank. South of Schumann, where the fold

becomes more nearly normal, both flanks will probably be found productive if penetrated deep enough. The surface structure indicates that the oil horizon plunges to a greater and greater depth under the whole region southeast of Casmalia Creek. The anticline south of Antonio is well defined and conditions favor the presence of oil on both this and the other anticline of the San Antonio terrace.

The main anticline on the coast north of Point Sal, already mentioned, is in the Vaqueros and is doubtless barren of oil. North of this locality the Monterey is decidedly bituminous, but no special circumstances point to the existence of petroleum in large quantity. It is quite possible that the region north of Mussel Rock, the next point to the north, would prove promising if the surface covering allowed the examination of the underlying formations and the determination of anticlines. The structure seems to cause the formations to plunge toward the north from the north end of the Casmalia Hills, and a fairly high portion of the Monterey may underlie the region at the mouth of the Santa Maria Valley.

BURTON MESA.

The plateau known as Burton Mesa is a region of numerous low folds in the Monterey. Along the coast the flinty shales are of low dip, but folded and contorted in a complex way. The folds indicated on the map are the most important ones, but whether or not they are perfectly continuous units across the mesa can not be definitely ascertained on account of the covering of sand over the shale. The mesa appears to be structurally a continuation of the region near Lompoc as much as it is of the Purisima Hills, although topographically it is a continuation of the latter. In the neighborhood of Pine and Santa Lucia canyons there is a thick series of shales striking far to the north of west and directing the structural lines across the Lompoc Valley as if to join those in that region that show a tendency to curve northward. West of Pine Canyon the strike changes. The Pine Canyon anticline shows this curving structure. It is a well-defined fold with broad summits and supports on its flanks a considerable thickness of shale. The dip ranges from 10° to 30°. A characteristic appearance of the shale and dip on the northeastern flank is shown in Pl. IV, *B* (p. 36). North of this fold occur a number of minor flexures and there is some doubt as to the continuity of the anticline mapped at the head of Oak Canyon with the well-defined fold near the coast in the vicinity of Canada Tortuga. A well-marked low anticline occurs near the coast north of Lompoc Landing and probably continues inland. It is probable that either one anticline of considerable importance or several small component flexures start across the mesa between Tangair and San Antonio Creek. The summit of all these anticlines so far

mentioned on Burton Mesa exposes hard shale that is low down in the Monterey, and it is probable that with the removal of all of the higher portion opportunity has been offered for the escape of the greater part of the oil from the basal beds.

A low anticlinal fold occurs in the northeast corner of Burton Mesa and plunges toward the southeast. As indicated by the dotted line on the map, it is possibly a continuation of the anticline south of Antonio before mentioned and another on the east edge of the mesa that is discussed in connection with the Purisima Hills. The evidence of folds in this northeastern portion of the mesa is scanty, but it is probable that where they occur accumulations of oil are present.

The brittle calcareous and flinty shale of the lower portion of the Monterey that is exposed along the coast edge of Burton Mesa is very bituminous. The petroleum slowly oozes out in some places and collects in tarry patches over the shale. Up Oak Canyon the shale is bituminous, pockets of tar being found in places in the flint on the surface. On the northern border of the mesa, near the point where the road to Lompoc comes up the grade, a 3-inch bed of bituminous sand was found traversing the shale fairly high in the formation.

PURISIMA HILLS.

FOLDS.

The Purisima Hills are formed by one broad anticline which has its axis on the south side of the summit of the dominating ridge. Through the major portion of this anticline's course, from the region north of the Hill wells to a point beyond Redrock Mountain, the beds lie almost horizontal on its summit, becoming gradually steeper up to an angle of 15° or 20°, or locally even 40°, within a mile or two from the axis. The general trend of this fold is more to the north of west than that of the Los Alamos or Santa Ynez valleys, but portions of it have a more westerly course, as at the west end, where it also becomes a steeper fold. At the east end it has the dominant northwest-southeast trend characteristic of this part of the hills and likewise becomes steeper. It is a fold plunging from either end toward the region at the head of Cebada Canyon, where the axis of the depression in the anticline occurs. This depression appears like a broad syncline crossing the anticline at right angles, with the deepest portion of its trough at this point.

The Purisima Hills anticline can not be traced farther westward than is shown on the map, but at the west end there seems to occur a structural offset to the northwest, a poorly exposed anticline about a mile from the end of the main fold being traceable for a short distance and seeming to mark the continuation of the general structure of these hills. There is a likelihood that oil may be found along this fold as well as along the main anticline.

FAULTS AND ASPHALT DEPOSITS.

A thrust fault is well exposed in two forks of Cebada Canyon, where the Monterey has been thrust to the southwest up over the Fernando. The dip of the fault plane is toward the northeast at an angle of about 30°. The movement has amounted to a few hundred feet. The fault zone seems to continue for a considerable distance toward the northwest and to be marked near the Wise & Denigan oil well No. 8 by large asphalt deposits occupying fractures in the Fernando that dip at an angle corresponding to that of the fault plane. The asphalt back of the Wise & Denigan well No. 1 is probably due to oil that has seeped through the same fractured zone and collected in the sandy capping.

The structure of these hills is further complicated by a prominent overturned anticline in the Monterey along the contact with the Fernando southwest of Los Alamos and by what appears to be a fault exposed near the mouth of Canada Laguna Seca. In this fault the Fernando limestone and sand are thrown down several hundred feet on the north, at the edge of the Los Alamos Valley.

In addition to the deposits above noted, asphalt occurs in great abundance south and east of Redrock Mountain, surrounded by a large area of very bituminous shale and burnt shale. Undoubtedly, an immense amount of petroleum has escaped here, but it is not probable that the supply is exhausted. On the contrary, the presence of this petroliferous material on the surface, coupled with the favorable structural conditions, points strongly to the existence of rich oil deposits beneath.

A large mass of asphalt is present in the much-fractured Monterey shale west of La Zaca Creek, and very bituminous shale approaching asphalt in character occurs on the creek south of Zaca station. The shale is bituminous throughout the zone of disturbance traversed by this creek south of Zaca. On account of the low position of the strata in the formation and the severe fracturing and folding that have taken place, it seems probable that the conditions have been favorable in this eastern portion of the Purisima Hills for the escape of much of the petroleum.

Small beds of bituminous sands interbedded with soft shale occur in the upper portion of the Monterey just east of Canada de la Puenta, about three-fourths of a mile south of the Los Alamos Valley; also on the north side of the Purisima Hills ridge, about 2 miles south of Harris. A small patch of shale that is saturated with bituminous material is exposed in the canyon followed by the road 1 mile south of the Los Alamos Oil and Development Company well No. 1, and the shale is bituminous in the neighborhood of the Todos Santos well.

CONCLUSIONS REGARDING FUTURE DEVELOPMENT.

The Purisima Hills anticlinal fold seems to offer a favorable location for oil wells along most of its south flank. Owing to the plunging of the fold toward its middle, lower and lower strata are reached as its extremities are approached. In the region mapped as Fernando, between the Hill wells and the head of Canada Laguna Seca, the summit beds of the Monterey are overlain by later sand and a well would have to be drilled to a great depth before reaching the oil horizon. East and west of that region the oil horizon probably approaches nearer to the surface. In the vicinity of Redrock Mountain, especially to the west of it, the conditions seem very favorable for the occurrence of oil. Farther east, near La Zaca Creek, a much lower portion of the Monterey is exposed and the rocks have been affected by considerable disturbance, so that it is less likely that large accumulations of oil will be found there.

AREA AROUND SANTA YNEZ.

The Santa Ynez anticline is a distinct steep fold exposed southeast of the town of that name. It supports on its flanks a thickness of at least 2,500 feet of calcareous and porcelaneous shales belonging to the lower portion of the Monterey. The dips at the axis range between 50° and 80°, but become lower toward either side. This fold is seemingly a structural continuation of that of the Purisima Hills, and it probably extends under the gravels of the region around Santa Ynez, its axis passing approximately under that town. But it is doubtful whether it is actually the same as either of the anticlines that are shown on the map as stopping indefinitely near the east end of the Purisima Hills. The terraced stretch between La Zaca Creek and Ballard seems from the fragmentary evidence obtainable to be in a way an undulating structural plateau formed of beds low in the oil-bearing shale, dipping at slight angles in various directions. It is probable that the structure of the Purisima Hills is here interrupted, but continued in a general way beyond by the Santa Ynez anticline. Owing to the low position of the beds in the formation, the chances for finding a considerable amount of oil along this anticline do not seem to be as good as farther west. No surface evidence of petroleum was seen. Any definite statements, however, in regard to the region between Los Olivos and Santa Ynez River and between La Zaca Creek and the east edge of the area mapped are hazardous, for the reason that the widespread terrace deposits obscure practically all of the structure.

SOLOMON HILLS AND AREA NORTH OF LOS OLIVOS.

GENERAL FEATURES.

Three anticlines dominate the structure of the Solomon Hills. These are, in order from west to east, the Mount Solomon anticline (first worked out and named by W. W. Orcutt), the Gato Ridge anticline, and the La Zaca Creek–Lisque Creek anticline. In addition to these there are at least three or four minor anticlines associated with the first named, and at least one north of that on Gato Ridge.

MOUNT SOLOMON AND ASSOCIATED ANTICLINES.

Structure.—The details of the northwest end of the Mount Solomon and associated anticlines are shown on the contour map (Pl. X, p. 92). Whether or not the anticline extending through the Santa Maria Oil and Gas and the Escolle properties should be considered the true extension of the Mount Solomon anticline, or whether the Hartnell anticline should be so considered, is impossible to decide with the data at present available. It is the writers' opinion that the Mount Solomon and Hartnell anticlines are the result of the same set of forces and should therefore be considered as one fold, but that the evidence offered by the data used in compiling the map favored the relations shown on Pl. X. The mapping of the Pinal, Hobbs, and Newlove anticlines is based almost entirely on evidence furnished by the drill, although certain superficial evidence strengthens the theory of their presence.

The southeastern portion of the Mount Solomon anticline gradually fades out into the southern flank of the Gato Ridge anticline, losing its individuality toward the southeast end of the Mount Solomon ridge. The northeastern flank of the anticline is much the steeper, dipping from 20° to 38° in the region of Mount Solomon, and gradually flattening out from that locality southeastward.

The Western Union anticline is a well-developed flexure with steep northern flank just south of the eastern group of Western Union wells, but its identity becomes more and more obscure as it fades into the southwestern flank of the Gato Ridge anticline in a similar manner to the Mount Solomon anticline, just south of the latter's southeast end.

The relations existing between the Mount Solomon and Schumann anticlines are vague, although it is certain that they are not in alignment and therefore can not possibly be one continuous feature. If the Hartnell and Mount Solomon anticlines are considered as one, the relations which exist between this united anticline and the Schumann anticline are exactly analogous to those which exist between the Mount Solomon and Gato Ridge and the Gato Ridge and La

Zaca Creek–Lisque Creek anticlines, viz, the adjacent anticlines are en échelon with each other, each plunging down past the end of its neighbor. Graciosa and Harris canyons, particularly the former, are the superficial reflection of the syncline between the ends of the Mount Solomon and Schumann anticlines, and Solomon Canyon and Canada de los Alisos occupy analogous positions between the Mount Solomon and Gato Ridge and the Gato Ridge and La Zaca Creek–Lisque Creek anticlines, respectively.

Asphaltum deposits.—Practically the whole top of Graciosa Ridge is capped by post-Monterey sandstones and conglomerates, which are heavily charged with asphaltum. Asphaltum also occurs as veins penetrating the Monterey and post-Monterey beds at the east end of the ridge, and a fine example of asphaltum veins and veinlets filling the joint cracks in the Monterey is to be seen beside the road leading up to the Santa Maria Oil and Gas (Squires) well No. 4. This occurrence of the asphaltum in the joint cracks of the shale gives a clew to the probable channels through which the oil migrated from the depths to the surface, and leads to the general conclusion that joint cracks are the reservoirs and channels of migration of the oil in many of the productive strata of this field.

Conclusions regarding future development.—It is obvious from a glance at the contour map (Pl. X, p. 92) and a perusal of the detailed description of the developed areas that practically all of the territory covered by contour lines is productive. The only part of the region about which the compiler of the map has any misgivings as to productiveness is that occupying a general synclinal position south of the great bend in the Mount Solomon anticline. These misgivings are partially alleviated, however, by the idea that probably the position of the territory in question on the flanks of Graciosa Ridge, which is, broadly, a quaquaversal fold or dome, may exert enough control on the oil to cause its collection there at least in paying quantities, if not in the remarkable measure found in other parts of this field. The region adjacent to the southeast end of the axis of the Mount Solomon anticline ought to be productive. The beds on the northeastern flank dip more steeply than those on the southwestern, and the first productive stratum is thought to be at a lower horizon in the shale on the former flank than on the latter, so that it is probable that the oil zone will be struck at a greater depth from the surface northeast of the anticline than southwest of it.

GATO RIDGE ANTICLINE.

Structure.—The Gato Ridge anticline extends from the top of the ridge just east of the mouth of Solomon Canyon to a point somewhere near the middle of the triangle formed by Canada de los Alisos, Cuaslui Creek. and Foxen Canyon. It follows very closely

the crest of the ridge between Canada del Gato and Solomon Canyon and for a considerable distance to the east is coincident with the highest topographic features. In general, the anticline plunges from the southeast toward the northwest, the lowest beds along its axis being exposed in the region of Canada Arena. The Fernando is the only formation exposed along the entire length of the anticline. With the exception of some diatomaceous beds which closely resemble and were at first mistaken for Monterey shale, the rocks exposed are sandstone and conglomerate.

The northwestern portion of the fold, from the Howard Canyon road northwestward, is a gentle arch with dips on the flanks rarely more than 5°, except northwest of Los Alamos, where the dips of some of the youngest beds exposed change abruptly from 3° or 4° to 15°. The northwestern extremity of the anticline fades off into the low slopes toward the Santa Maria Valley. From Howard Canyon eastward the southerly dip increases rapidly in steepness until in the region of Canada de los Coches it attains a slope of 25° to 35°, the steepest dip being at the junction of the canyon last named and Canada Arena. Although the southerly dip increases in steepness toward the east along the anticline, the dip of the northern slope becomes less, ranging from 12° or 15° in the region of Howard Canyon to 3° or 4° just west of Canada Arena, and finally changing to a gentle southward slope in the region of Cuaslui Creek, thus fading into the southern flank of one of the folds emanating from the region at the head of Round Corral Canyon and Asphaltum Creek. In the region of Cuaslui Creek the flexure is therefore not a typical anticline in the regularly accepted sense, the horizontal being used as datum, but in every other way it conforms to the characters of such a structural feature.

On the ridge north of the central portion of Canada del Gato and extending indefinitely northwestward out into the Santa Maria Valley a mile or so southwest of Gary is a low anticline, the southeastern end of which merges into the almost horizontal northern flank of the Gato Ridge anticline. At no place along its course is this structural feature well developed, although it appears to be fairly persistent for a considerable distance.

Evidences of petroleum.—Very little surface evidence of the existence of petroleum in the Gato Ridge anticline is to be had along its course. Near its axis in Cuaslui Creek and north of the head of Howard Canyon, however, the Fernando shale is slightly bituminous. The Pezzoni well, in Canada Arena; the Williams well, near Canada del Gato, 1½ miles west of the Howard Canyon road, and the Palmer Oil Company's well No. 1, 1 mile west of the lower part of Canada del Gato, all approximately a mile north of the anticline, offer indisputable evidence of the presence of the oil-bearing rocks

along a considerable extent of its northern flank. In the region of the Pezzoni well an unproductive oil and gas bed is encountered at about 1,200 feet below the surface, immediately followed by a diabase or lava rock in which the ferromagnesian minerals have been weathered to serpentine. In the Williams well the same or a similar oil and gas bed occurs much lower. The well was abandoned owing to the terrific gas pressure, which heaved heavy tar up into the hole and stopped operations. The Palmer well is productive, yielding oil of 16° or 17° gravity. Although not directly associated with the minor anticline northeast of Canada del Gato, the asphaltum occurring at Fugler Point, 1 mile north of Gary, is important in indicating the probable presence of petroleum in the upper end of the Santa Maria Valley.

Conclusions regarding future development.—The region north of the Gato Ridge anticline, from the vicinity of Cuaslui Creek westward to a point at least a mile beyond the Howard Canyon road, is underlain by strata so nearly horizontal as to preclude their containing very productive accumulations of petroleum. North and northwest of this region, however, especially near the axes of the Gato Ridge anticline and the anticline north of it, the indications are good for productive wells. The conditions for the accumulation of petroleum are also good along and just south of the axis of the Gato Ridge anticline in the vicinity of Cuaslui Creek and from this locality westward to the upper portion of Canada de los Coches. The same might be said of the immediate vicinity of the row of prominent knobs which extend in a straight line northwestward for 5 miles from a point about a mile north of Los Alamos, and possibly also, but in a less degree, for the territory between these knobs and the axis of the anticline. These knobs mark an abrupt change in the dip of the beds from 3° to 12° SW. to 35° or 40° or possibly more, in the same direction. Wells would have to be sunk to a considerable depth along this last-mentioned line to reach the oil horizons, but if oil was encountered at all it would probably be in such quantities as to pay for the deep holes.

LA ZACA CREEK–LISQUE CREEK ANTICLINE.

Structure.—The La Zaca Creek–Lisque Creek anticline extends from the ridge southeast of Canada del Comasa southeastward at least as far as the edge of the Lompoc quadrangle east of Santa Agueda Creek. Its course is practically straight except at the northwestern extremity, which bows around toward the southwest and is en échelon with the east end of the Gato Ridge anticline. The dips along the axis are low in both directions, but distant from it they are much steeper, being as high as 30° or more to the northeast on the second

ridge east of Figueroa Creek, as shown in Pl. VI, *A* (p. 46), and 30° SW. at the junction of Figueroa and Lisque creeks.

Conclusions regarding future development.—No indications of petroleum were noticed in proximity to this anticline, and it is almost certain that no productive wells will be developed on that part of it which lies within the Lompoc quadrangle, with the possible exception of a small area at its west end. There are good reasons for believing that the oil-bearing beds are absent from most of its northern flank, and if present under certain portions of its southern flank they lie at such a depth as to preclude their successful exploitation.

SUMMARY OF CONCLUSIONS REGARDING FUTURE DEVELOPMENT.

There can be no doubt that the region treated in this report is one of great promise. The structural and other conditions in general favor not only much more extensive development of the territory that has already been tested, but also the development of new fields. It must be borne in mind continually, however, that absolute determination, by work on the surface, of the possibilities of occurrence or nonoccurrence of oil in any one locality is not possible. The best that can be done is to calculate the degree of probability on the basis of a summation of surface indications and structural conditions.

The following is a list of the tracts that appear especially to invite testing with the drill. Most of them have been discussed in the foregoing pages:

North and northeast of Sisquoc post-office, along anticlines.
General region east and west of Tepusquet Creek.
Indefinite area west of Gary, about Fugler Point.
Santa Rita Hills anticline.
Near the coast north of Schumann Canyon.
Schumann anticline in southeastern part of Casmalia Hills.
Two anticlines on San Antonio terrace.
Questionable region at mouth of Santa Maria Valley.
Northeastern portion of Burton Mesa.
Purisima Hills anticline, more especially the south side.
Anticline at head of Santa Lucia Canyon.
Region about Mount Solomon and related anticlines.
Along Gato Ridge anticline and south of it between Canada de los Alisos and Canada de los Coches.
Row of knobs extending 5 miles northwestward from a point about 1 mile north of Los Alamos and the territory between these knobs and the Gato Ridge anticline.
Region northwest of the head of Howard Canyon, especially along the axis of the anticline south of Gary.
Arroyo Grande field. (See pp. 107–108.)

DETAILS OF THE DEVELOPED TERRITORY.

DEFINITION OF FIELDS.

In the following paragraphs are discussed the more important details regarding the structure, geology, oil zones, oil, and production in the areas in which development is well under way. These areas within the Lompoc and Guadalupe quadrangles fall naturally into two fields—the Santa Maria field and the Lompoc field. The former covers the whole territory between the Los Alamos and Santa Maria valleys, and the latter is used to designate the region south of the Los Alamos Valley. A third, the Arroyo Grande field, covering the territory north and northwest of the town of that name in San Luis Obispo County, lies to the north of the region mapped, but is briefly discussed. A note on the Huasna field, east of Arroyo Grande, is also appended.

SANTA MARIA FIELD.

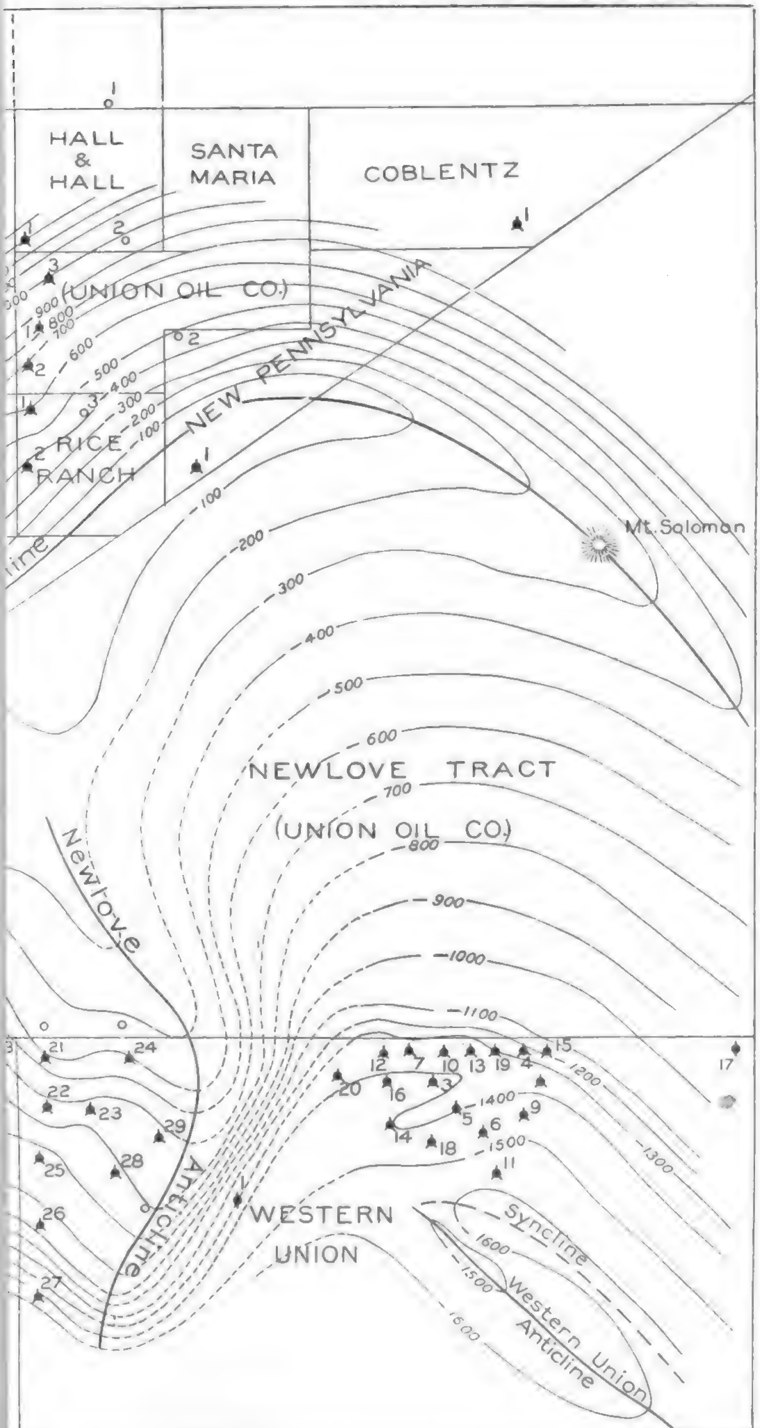
CONTOUR MAP.

WHAT IT SHOWS.

The contour map of the Santa Maria field (Pl. X) shows the boundaries of the different properties, the approximate location of all the wells, and the general structure of the field. The structure is indicated by contours showing the distance below sea level of a hypothetical horizon, zone, or bed, which just reaches sea level at the highest part of the axis of the Mount Solomon anticline. The contour interval is 100 feet. By means of this map the direction and amount of dip of the strata in the oil-bearing Monterey shale may be calculated for any point in the field, as the contour lines show the direction of strike (to which the dip is at right angles), and the horizontal distance between any two contours is the distance through which the beds dip 100 feet at that particular point.

BASIS OF CONTOUR MAP.

The property lines were sketched from a map kindly furnished by Frank M. Anderson. The wells were located in the field by the eye, supplemented by pacing and in some instances by information furnished by the managers of properties. The log of every well in the area either finished or down any considerable distance in August, 1906, was used in the determination of the structure and the compilation of the data concerning the oil zones. All additional information available up to January 15, 1907, has been used in a revision of the contouring. All of the obtainable surface evidence of dip and strike of the beds was also used in the preparation of the map. In every case where the surface and well-log evidence were at variance


HALL & HALL
SANTA MARIA
COBLENTZ
(UNION OIL CO.)
NEW PENNSYLVANIA
RICE RANCH
Mt. Solomon
NEWLOVE TRACT
(UNION OIL CO.)
Newlove
Anticline
WESTERN UNION
Syncline
Western Union Anticline
100
200
300
400
500
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700
800
900
1000
1100
1200
1300
1400
1500
1600

the latter was followed. In the Fernando formation, which unconformably overlies the Monterey shale, it was natural to expect variance with the structure in the Monterey, but even here the surface evidence more often supported than contradicted the evidence obtained by the drill.

DIFFICULTIES OF PREPARATION.

After carefully plotting all the logs on a uniform scale it was found that the greatest obstacle to overcome in the preparation of the contour map was the correlation of strata from one well to another and from one part of the field to another. The difficulties of such correlations are doubtless familiar to anyone who has tried to work out the underground structure of any of the California fields. The Santa Maria field offers as much encouragement to successful study and mapping of the underlying oil-bearing formations as any other so far examined by the senior author, and so the effort has been made to delineate on the map all the details of structure furnished by the data available, and to supplement these details by showing for the untested areas what seem to be the most likely conditions of underground structure. It is very easy to make an ambiguous statement which will apply equally well to any conditions exposed by future development, no matter what they may be; but it is impossible to make an ambiguous map. However, it is deemed advisable to show the information in hand, incomplete as it is, on a map. Future development will doubtless add much to our knowledge of this field, and will show the inaccuracies of the contouring as here presented, but it is hoped that the benefits which may accrue to the operators from a knowledge of the general structure of the field will compensate in a measure for the errors in detail which are to be expected in a map based on data so incomplete.

THE WELLS.

AREAS DISCUSSED.

For convenience of discussion the proved portion of the Santa Maria field has been roughly divided into six areas, based largely on the geographic position of the wells. The following are the areas discussed: Hall–Hobbs–Rice ranch; Pinal–Fox–Hobbs; Pinal–Folsom–Santa Maria Oil and Gas–Escolle; Hartnell–Brookshire; Graciosa–Western Union; and eastern Western Union.

OIL ZONES.

Although in many instances detailed correlation from one well to another is impossible, four fairly well defined oil zones are believed to be recognizable in the Santa Maria field. Of these at least two are found in practically every part of the field, although all vary

more or less in thickness, composition, and yield from well to well. The most persistent zone in that part of the field which is best developed at the present time is the second, or B zone. Above this in many of the wells is zone A; in others zone C is penetrated below it. The upper zone in the eastern group of Western Union wells, although above what is supposed to be the horizon of B, is probably considerably above the A zone of the northern part of the field, where it appears to have no correlative.

With the exception of the lowest zone in the wells in the eastern part of the field and of a few others mentioned in the detailed discussion of the local areas, the oil zones appear to represent fractured portions of the shales, the interstices in the breccia or possibly joint cracks in the beds being the reservoirs for the storage of the oil. The exceptions to the brecciated productive zones are apparently typical sands and gravels.

HALL-HOBBS RICE RANCH AREA.

LOCATION AND STRUCTURE.

The area here discussed comprises the California Coast, Meridian, Coblentz, Santa Maria Oil Company (Keyser), Hall & Hall, New Pennsylvania, Rice ranch, and Dome properties and the northeastern part of the Hobbs lease, and occupies the ridges and canyons which extend northward from the east end of the main Graciosa Ridge. The wells are located on the northwestern flank of the Mount Solomon anticline, at or immediately northwest of the territory, in which it swings from a northeastward to a southeastward trend. In addition to the main anticline there appear to be one or more local flexures involved in the structure of the field, the Hobbs anticline and the syncline between it and the Mount Solomon anticline being the most prominent. The characteristics and extent of these features as they are believed to exist are portrayed on the contour map (Pl. X).

GEOLOGY OF THE WELLS.

Nearly all the wells in this area, with the exception of the Hall, Meridian, and Coblentz start down in the Monterey shale. Those farthest away from the top of the ridge, other things being equal, have to penetrate farthest through the Fernando clay, sand, and conglomerate. Up to the present time the greatest thickness of the Fernando penetrated before reaching the shale is 650 feet, and much trouble was experienced in going through it in this well, the formation being mostly sand. From the top of the Monterey shale to the bottom of the wells the rocks are largely blue and brown shales, with only here and there interbedded hard "shell" layers. In fact,

one log reports "no shell" until the first oil zone is reached. Wherever "shell" is penetrated accumulations of gas or oil or both are generally encountered. The shale seems to be somewhat more sandy in this area than farther west or in the Graciosa-Western Union region.

Three oil zones are recognizable in the area under discussion, although practically all the strata from the top of the uppermost zone to the bottom of the lowest are more or less petroliferous at one point or another.

The first productive zone (A) is penetrated at a depth of 1,600 to 2,100 feet, varying according to the position of the well geographically and relatively to the axis of the anticline. Its top is from 550 to 700 feet above the top of zone B in this area. Zone A is productive for a distance in the wells of 20 to more than 500 feet. Of course this does not mean that the beds are productive in any one well for the whole distance of 500 feet, but that throughout the zone alternating barren and productive beds occur at such close and as a rule irregular intervals as to preclude their practical differentiation. The productive measures in this first zone consist both of hard fractured shale or "shell" and more or less porous sandy layers. In at least one of the wells the oil accumulates only under the hard "shell" layers. Zone A is the only one penetrated by some of the wells farthest away from the anticlinical axis. In these wells it appears to be much more petroliferous than in wells higher up on the fold.

The second oil zone (B) is from 550 to 700 feet below the top of zone A, and its upper limit is about 300 or 400 feet above the top of zone C, although it can hardly be said to be distinct from C in all the wells, so rich in oil are some of the intervening strata between them. True sands of medium grain, in addition to the productive hard shale, yield the oil in this zone.

The third oil zone (C) is encountered in some of the deeper wells nearest the axis of the main anticline. This zone has been penetrated for as much as 150 feet, the whole distance being very rich in petroleum. It is overlain by a considerable thickness of black shale, also more or less petroliferous, between which and the rich zone is a thin, hard "shell" layer. The oil-yielding rock is a true sand, coarse in places and even becoming pebbly toward its base in certain portions of the area. To the coarseness of the material is doubtless due the great productiveness of the zone.

PRODUCT.

The oil in the Hall-Hobbs-Rice ranch area runs from 26° to 29° Baumé and is dark brown in color. Gas accompanies the oil and also occurs isolated under some of the more impervious "shell" layers in the shale. No water is reported in any of the wells.

The production of the wells ranges from 300 to something over 2,000 barrels per day. Those wells which penetrate the lowest or C zone are the best producers. It is said that where a number of wells are located comparatively near together the production of each well is largely dependent on whether or not the adjacent wells are producing, a fluctuation of 50 per cent resulting from this cause in some instances.

PINAL-FOX-HOBBS AREA.

LOCATION AND STRUCTURE.

The area comprising the Fox lease, the southwestern part of the Hobbs lease, and the northeastern portion of the Pinal property, occupies the ridge and two adjacent canyons which extend northward from the central portion of Graciosa Ridge. The wells are located in an area of considerable structural disturbance caused by the development of two local anticlines on the northwestern flank of the main Mount Solomon anticline. These two minor flexures have been named after the companies under whose property they are best developed. Although the position assigned to them on the map is more or less hypothetical, the evidence in favor of it is fairly complete, and their location explains some of the variations in production of adjacent wells.

GEOLOGY OF THE WELLS.

Practically all the wells within this area start in the Monterey shale, and this is the prevailing formation to their bottoms. Certain portions of the shale are burnt to a brick-red color by the combustion of their hydrocarbon contents, the burnt shale being encountered as low as 330 feet in one of the wells. The burning has so hardened the shale in places as to render drilling in them more difficult. A hard limestone "shell" layer was encountered in one of the wells just above the second (B) oil zone. Tar or asphaltum occurs in some of the wells at a depth of about 600 feet, in others at various depths from 200 to 1,200 feet. The tar is in many wells associated with black shale. Gas accumulations under "shell" and other impervious layers are of common occurrence both in the oil zones and locally in the barren overlying shale. Water is encountered in some of the wells at depths ranging from 150 to 270 feet. This occurrence is noteworthy, as the wells in the group to the east are, so far as known, quite free from water in the shale. Its occurrence in the Fernando sands and conglomerates is to be expected, but its presence in sands interbedded with the shale is unusual for this field.

The first oil zone (A) is penetrated in the wells in this area at depths ranging from a little more than 1,600 to 2,650 feet, or between 400 and 600 feet above zone B. (See Pl. X, p. 92.) Petroliferous strata occur in some of the wells above this horizon, but they are of

little consequence as regards production. The thickness of zone A in the wells ranges from 8 or 10 to nearly 150 feet, but several more or less important oil-bearing zones lie between this and the next lower (B) zone. The productive measures of zone A consist largely of brown shale, probably seamed or jointed in such a way as to afford a reservoir for the oil, although certain of the wells may obtain their product from fine-grained sands interstratified with the shale.

The second oil zone (B) is the most important one in this area, although it is underlain over at least a part of the area by zone C, which is apparently even more productive. The thickness of zone B is variable, but most of the wells penetrate from 50 to 150 feet of productive strata at this horizon. The oil-bearing beds are similar to those of zone A and appear to consist largely of hard shales, with some fine sands, although some excellent examples of a true siliceous sand are obtained in many of the wells. A hard limestone "shell" overlies zone B in one well.

The third oil zone (C) is penetrated by some of the deeper wells at a depth of about 300 to 400 feet below zone B. In one of the wells zone C appears to be missing, although a good flow of oil is reported from the same hole about 500 feet below where it should occur.

Water underlies oil-zone B in one of the wells and zone C in another. This occurrence of water below the oil, so common in most fields, is very rare in this one. Whether or not in the course of time water will follow up the oil in the productive zones is something that will be awaited with a great deal of interest. Some of the wells in the Santa Maria field have been stopped in the midst of productive strata for fear of encountering water farther down, but whether or not these fears were well founded has never been established.

PRODUCT.

The oil from this group of wells is of a dark-brown color and ranges in gravity from 24° to 28° Baumé, the lighter oil usually occurring in the wells nearest the main anticline; the average gravity is between 25° and 26°. Much gas is associated with the oil in all the wells.

The production of the individual wells ranges from 60 to 1,000 barrels per day, the latter amount coming from a hole very eccentric in its behavior, as shown by its yield of 200 barrels on some days and as high as 1,000 on others; the average daily production for this well is 300 barrels. With the eccentric well omitted, the maximum production is about 500 barrels per day. One well which produced 150 barrels from zones A and B added 350 barrels to its output when deepened to zone C.

PINAL-FOLSOM-SANTA MARIA OIL AND GAS-ESCOLLE AREAS.

LOCATION AND STRUCTURE.

The area discussed in this section comprises the Folsom lease, the southern part of the Pinal property, the central and southern portion of the Santa Maria Oil and Gas lease, and the Escolle property of the Union Oil Company. The wells are located on the west end of Graciosa Ridge and in the canyons on its sides. The region is largely covered by the Fernando sandstone and conglomerate "cap rock," although the Monterey shale is exposed in the side canyons. The structure underlying this part of the field is comparatively simple so far as known, the main Mount Solomon anticline, which plunges northwestward through its center, being the only fold of consequence immediately affecting the area. The mapping of the anticline near Escolle well No. 3 is based entirely on the evidence offered by the well logs, which is at variance with the northwesterly dips in the Fernando in the vicinity of Escolle wells Nos. 2 and 3.

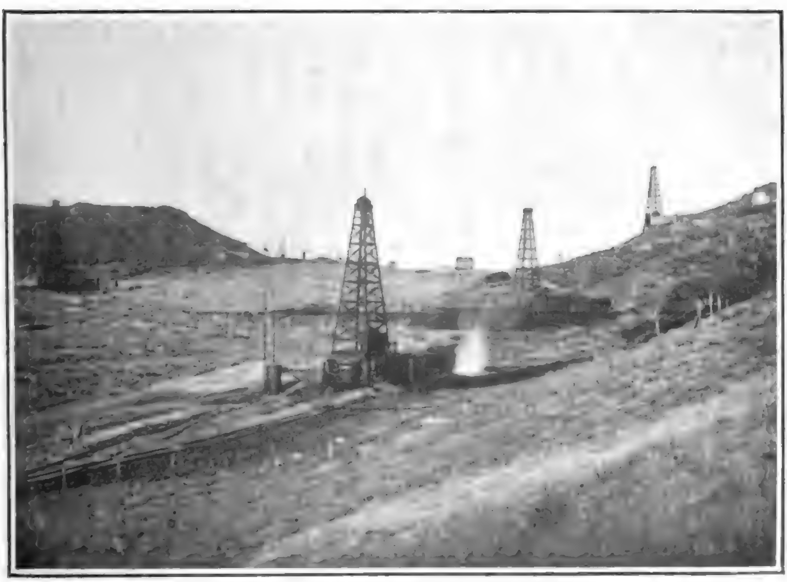
GEOLOGY OF THE WELLS.

Those wells which start in the Fernando remain in this formation for distances ranging from a few feet to nearly 300 feet, the strata penetrated being sand and conglomerate. In the region of Escolle well No. 1 and Folsom well No. 1 the Fernando appears to be exceptionally deep, extending nearly 300 feet below the surface, and to consist largely of conglomerate. One of the wells reports red conglomerate at 30 to 90 feet below the surface; whether this is burnt shale so hardened as to come out of the well in fragments of considerable size or whether it is true water-worn material is not known. Asphaltum is reported at the base of the Fernando in some of the wells, and may also be seen at the contact between the Monterey shale and overlying beds at many places in this area. (See Pl. XI, *A*.) The channels through which this material has escaped from the shale are undoubtedly joint cracks, as veins of the hardened asphaltum may be seen in the shale beside the road leading up to Santa Maria Oil and Gas (Squires) well No. 4 and at other points in the field. From the base of the Fernando to the bottom of the wells the strata penetrated are practically all shale with a few hard "shell" layers, under which occur accumulations of gas and locally of oil.

A zone in which "shells" appear to be particularly abundant immediately overlies the first oil zone. Traces of tar and asphaltum are also reported in the shale at various depths. Two zones in which many hard limestone "shells" layers are encountered are reported from some of the wells; one of these is about 500 feet above the second oil zone (B), and the other immediately underlies it.

A. DARK-COLORED FOSSILIFEROUS BREA DEPOSIT OVERLYING MONTEREY SHALE.

Graciosa Ridge at Folsom well No. 3; Pinal camp on left and Santa Maria Valley in distance. Looking north. Photograph by Ralph Arnold.



B. SADDLE IN MONTEREY, FERNANDO, AND PLEISTOCENE BEDS.

Graciosa Ridge at Hartnell well No. 1, near Orcutt; Pleistocene on left, Fernando (Pliocene) in upper right, Monterey (Miocene) in saddle. Looking east. Photograph by Ralph Arnold.

The first oil zone (A), which lies from 250 to 500 feet above zone B, is struck at depths ranging from 1,400 to 2,450 feet. Its thickness ranges from a few feet to about 50 feet; according to the logs it is lacking in some of the wells, the first oil being encountered in zone B. The oil-bearing strata in zone A are largely shale, which afford a reservoir for the oil, probably on account of their fractured condition. Beds of fine sand in this zone may also contain some of the petroleum.

The second oil zone (B), occurs at depths of 1,950 to 3,150 feet and is penetrated by all of the wells in this area. It ranges in thickness from nearly 50 to about 250 feet, in the wells; one of the wells, however, is said to encounter petroliferous beds intermittently from the top of zone B for a distance of 550 feet downward. The oil-bearing strata consist of alternating layers of hard shale and fine sandstone.

The third oil zone (C), occurs from 500 to 600 feet lower in the wells than zone B and consists of two parts, each from 25 to 50 feet thick, separated by a layer of shale of variable thickness; in one of the wells, however, the intervening shale is missing and the strata are richly impregnated with oil from the top of the zone for a distance of 250 feet downward, to a point where a 3-foot layer of water sand limits the productive zone. In practically all the wells in the field zone C is very rich, and nearly all the wells tapping it are fine producers.

PRODUCT.

The oil obtained in the area under discussion averages somewhat better than that in the area to the east, and has a gravity of 26° to 28° Baumé, with an average somewhere between 26° and 27°. As is common in other portions of the field, the gas pressure in most of the wells is high.

The production of the individual wells ranges from 100 to 2,700 barrels per day, the well yielding the latter amount being said to have had an initial daily output of 5,000 barrels for a short time. In one series of wells those down the dip are more productive than those nearer the axis of the anticline, the variation being at least partially accounted for by a thickening of the oil zone away from the axis.

HARTNELL-BROOKSHIRE AREA.

LOCATION AND STRUCTURE.

The area comprising the southern portion of the Hartnell tract and Brookshire property and the southeastern portion of the Radium lease is located on or adjacent to the ridge running northwestward from a point near the west end of Graciosa Ridge, and in the broad valley to the south. The major structural feature developed in the

beds underlying the area is a northwestward-plunging anticline which is here called the "Hartnell." There is both surface and underground evidence of its presence, but its exact location is, of course, only conjectural. As will be noticed on examining the map (Pl. X, p. 92) the northern flank of the anticline is much steeper than the southwestern, this fact apparently having a direct bearing on the productiveness of the wells penetrating this flank.

GEOLOGY OF THE WELLS.

The surface distribution of the formations in the immediate vicinity of the little swale on the ridge in which Brookshire wells Nos. 3 and 4 are situated is very interesting. The bottom of the swale is Monterey (Miocene) shale; unconformably overlying this on the south is fossiliferous Fernando (Pliocene) sandstone and conglomerate; immediately north of the swale is terrace-deposit (Pleistocene) sandstone. (See Pl. XI, *B*.) It has been suggested that such a condition is most easily explained by the presence of a fault through the swale, the downthrow being on the north. The logs of the wells in the immediate vicinity, however, offer evidence that such is not the case, but that the underlying Monterey strata, followed almost immediately north of the swale by fossiliferous Fernando beds, plunge steeply northward and are overlain unconformably by the low-dipping or practically horizontal terrace beds which are exposed on the ridge north of the swale. Some of the wells starting in the post-Monterey formations penetrate sand and gravel for a distance of more than 600 feet before entering the Monterey. Limestone, probably corresponding to the limy layers associated with fossiliferous beds at the base of the Fernando in the railroad cut north of Schumann, is reported as occurring next to the Monterey shale in one of the wells. Water is encountered in gravel at various horizons in the Fernando between the depths of 150 and 600 feet. Hartnell well No. 3 and Brookshire well No. 1 (the latter about half a mile northeast of the area under discussion), which penetrate the water-bearing Fernando, are used as water wells. From the base of the Fernando to their bottoms the wells penetrate blue and brown shale, and very rarely fine sandy layers. "Shell" strata, many of them underlain by gas and some by oil and gas, are encountered here and there throughout the shale.

The first oil zone (A) occurs about 400 feet above zone B, is struck at depths ranging from 2,150 to more than 3,000 feet, and is said to be from 2 to 5 feet thick. On examination of the material coming from this and the underlying productive zones, it is quite apparent that the oil must come from the joint cracks or interstices between the fragments of more or less fractured shale, as no true sands of sufficient coarseness to allow the rapid transmission of the oil have been encountered in the productive zones in the wells of this group.

Between the first zone and the one that has been recognized as the second, or zone B, are one or more productive zones 2 to 15 feet thick. No two wells show the same sequence of these zones and they probably represent places of local fracturing.

The second oil zone (B) is thought to be fairly constant throughout the area. It consists of alternating barren and productive layers of shale, some of the productive layers being from a few feet to as much as 20 feet thick. Below the main or upper part of this zone are other productive layers, some at least 200 feet below zone B. The oil-bearing measures in these zones, as in zone A, are probably nothing more or less than fractured portions of the shale.

PRODUCT.

The oil from the wells in this area runs from 24° to 26° Baumé, and is dark brown in color with the exception of that from one of the wells, which is said to be a reddish emulsion of oil and water. All the wells show much gas, the best producers, especially, being under heavy pressure.

The production of the individual wells in this group ranges from an initial output of 12,000 barrels per day in one well to a daily average of 150 barrels in another. The following statement concerning the production of Hartnell well No. 1, the greatest producer in the California oil fields, has been kindly furnished by Mr. Orcutt, of the Union Oil Company:

Well (Hartnell No. 1) started to flow over derrick through 8¼-inch and between this and 10-inch casing December 3, 1904. Gas pressure was very heavy, estimated at 400 pounds per square inch—was probably much higher, however. Oil was measured in an open ditch by use of a miner's-inch measuring box, and showed 31 miner's inches, or about 12,000 barrels per day. The flow continued for about sixty days and gradually weakened. September 1, 1905, the well was doing 3,069 barrels per day.

The oil was stored in earthen reservoirs, and the production to the above date is estimated at 1,500,000 barrels from this well alone. Up to August 15, 1906, the total production for the well was something over 2,000,000 barrels.

The gas accompanying the initial flow of oil was estimated at 4,000,000 cubic feet per day. After the well had been gotten under control it furnished gas for running 20 boilers for well-drilling rigs, and in addition supplied the town of Orcutt (population about 200) with gas for domestic purposes. At the present time it is still yielding a constant flow, which is used for many purposes in Orcutt.

GRACIOSA-WESTERN UNION AREA.

LOCATION AND STRUCTURE.

The wells at the northeast corner of the Graciosa and northwestern corner of the Western Union properties are located on the point of the ridge which runs southward for more than a mile from the main Graciosa ridge. The structure of the beds underlying the developed area is apparently simple, as they are on the southwestern flank of the hypothetical Newlove anticline. At least two minor

folds occur on this flank, one apparently passing through Western Union wells Nos. 21 and 22 and the other occurring from three-eighths to five-eighths of a mile farther northwest. The Newlove anticline as shown on the map is wholly hypothetical. It is the expression of the most plausible explanation of the relationship which is supposed to exist between the known Graciosa-Western Union and the eastern Western Union well areas. The surface evidence of the structure consists of a 10° SE. dip in the Fernando beds just north of the Graciosa wells, together with some more or less uncertain dips in the Monterey toward the head of the ridge, approximately parallel with which the anticline is supposed to run.

GEOLOGY OF THE WELLS.

The wells all start in the sands of the Fernando, penetrating this formation for 70 to 300 feet. No water is reported from this sand, but asphaltum is said to have been found at its base in one of the wells. From the base of the Fernando to the top of the main productive zone the formation consists of blue and brown shales with many hard "shell" layers, some beds of sticky shale, and rarely a little sandy material. Streaks of asphaltum are reported as occurring in the shale in some of the wells, and in others gas is present under some of the "shells."

The first oil zone (B of the northern part of the field) is reported from only one well, where it is nearly 200 feet thick and is encountered at a depth of about 2,075 feet. Gas is associated with the oil in this zone.

The second and important oil zone of this area (C) is struck at depths ranging from 2,670 to something more than 3,800 feet, and lies about 600 feet lower in the wells than zone B, which is apparently unproductive in most of the wells. According to the data in hand, the productive zone ranges in thickness from 18 to about 240 feet and consists of alternating light and dark flinty shales interbedded with varying amounts of sandy shale. No true sand, as ordinarily implied by the name, occurs in the productive zone of this area, so far as the writers were able to learn.

PRODUCT.

The oil from zone C runs from 25° to 27° Baumé, averaging well up between 26° and 27°, and has a brownish color. It comes from the wells at a temperature of about 95° F. and is usually accompanied by much gas. Certain of the wells. however, are said to show a comparatively low gas pressure.

The production of the individual wells ranges from 300 to 3,000 barrels per day, the flow of many being unusually strong. None of the wells have been allowed to produce up to their full capacity,

owing to the lack of storage and transportation facilities, so that even had they been down long enough for a thorough test (which is hardly the case, inasmuch as nearly all have been finished since 1904) no definite conclusions could be drawn concerning their lasting properties.

EASTERN GROUP OF WESTERN UNION WELLS.

LOCATION AND STRUCTURE.

The eastern wells of the Western Union Company are located near the head of one of the branches of the broad valley which extends east-northeastward from Harris Canyon, at Blake, and are about 5 miles southeast of Orcutt. They are from one-half to three-fourths of a mile east of the west property line of the company and close to the north line. Slightly more than half a mile to the northeast of the wells is the axis of the Mount Solomon anticline, from the southwestern flank of which the wells derive their oil. The structure in the immediate vicinity of the wells, as indicated by the logs (see Pl. X, p. 92), is more or less complicated, the general strike of the beds apparently changing abruptly from northwest to southwest immediately northwest of the group. Furthermore, a local flexure with northeast-southwest strike immediately underlies the developed territory, and a pronounced anticline (here named the "Western Union") with a steep northeastern flank lies just to the south. There is no surface evidence of the northeast-southwest disturbance, but the Western Union anticline is plainly to be seen in the Fernando beds. The dip of the beds on the southwestern flank of this fold ranges at the surface from 15° at the west end of the hill south of the wells to 10°, and possibly much less, one-half mile to the southeast. The maximum northeasterly dip of 45° occurs south of well No. 18, but the slope rapidly decreases both to the northwest and southeast. As nearly as could be ascertained from the available data, the production of the wells in this group supports the anticlinal theory of the accumulation of petroleum—that is, for an equal thickness of productive zone the wells near the axis of the anticline in the local flexure are more productive than those farther away from it.

GEOLOGY OF THE WELLS.

The wells start in soil, but soon enter the clay, sand, and conglomerate layers of the Fernando, which is the surface formation in this part of the field. The Fernando beds are penetrated for 100 to 250 feet, varying with the location of the well, the wells on the north, as would be expected after an examination of the surface geology, passing through it in the shortest distance. Water and quicksand were encountered in at least two of the wells in the lower portion of the Fernando; in another, asphaltum occurs at the base of the formation. From the base of the Fernando to the first oil zone the wells penetrate

blue and brown shales, largely the latter, interstratified with hard "shell" layers, under some of which are accumulations of gas.

The first oil zone is struck at a depth of 1,200 to 1,800 feet, and ranges in thickness from 12 to 75 feet, although in some of the wells sands are encountered at intervals for at least 250 feet below the top of the first sand. The oil sand is as a rule rather fine grained and is accompanied both above and below by shale and rarely by shell. In some of the wells the oil zone appears to be practically continuous sand for its entire thickness; in others, alternating sand and shale layers furnish the oil.

A second oil zone occurs about 1,200 feet below the first, the entire distance between the two being occupied by shale, with a few hard "shell" layers. Very little oil occurs at this horizon.

A third oil zone about 150 feet thick is penetrated 2,100 feet below the first, the formation between the second and third zones being practically all shale. Comparatively little oil was obtained from this zone in this part of the field, although it is thought to be the same as the one which is so productive in the Graciosa Western Union area only half a mile to the west. This may be accounted for by the general synclinal position of the eastern group between the Mount Solomon and hypothetical Newlove anticlines.

PRODUCT.

The oil in the first productive zone has an average gravity of about 19° Baumé and is very dark colored. Gas is associated with the oil, but no water has so far been reported from any of the wells.

The production of the wells in this group ranges from 5 to 154 barrels per day. The yield of some of the wells is fairly constant, showing only a small decrease in average daily output over a considerable number of months; in others, however, the yield is fluctuating.

LOMPOC FIELD.

LOCATION.

The developed territory within the Lompoc field, on which the following discussion is based, lies on the flanks of the Purisima Hills between the Cebada Canyon and Santa Lucia Canyon roads. Within it are located the Logan well of the Los Alamos Oil and Development Company; the Hill, Wise & Denigan, and Eefson wells of the Union Oil Company; and the abandoned wells of the Todos Santos, Coast Line, and Barca oil companies.

STRUCTURE.

The dominant structural feature of the field is the main anticline of the Purisima Hills. From surface evidence the location of the

anticline is believed to be that shown on the map (Pl. I, in pocket); from the evidence offered by the logs of the Hill and Logan wells the axis of the anticline, so far as it affects the oil-bearing beds of this part of the field, might better be drawn through Hill well No. 1, extending westward and eastward (swinging to the north in both directions) to the points where the "surface" anticline passes from the Fernando to the Monterey. In either location, however, the anticline has a steeply dipping northern flank and a low-dipping and probably undulating southern flank.

A fault, clearly seen on the east side of Cebada Canyon and traced by deposits of asphaltum over portions of the rest of its course, extends from a point a short distance east of Cebada Canyon northwestward at least as far as the brea deposits near Wise & Denigan well No. 1. This is clearly a reverse fault in the Cebada Canyon region, supposed Monterey diatomaceous shale being thrust up on the north over Fernando sandstone which lies south of the line, the dip of the fault plane being about 30° toward the north. Mr. Orcutt suggests that this fault probably causes the difference in yield between Hill wells Nos. 2 and 3. The sand is struck about 700 feet lower in No. 3 than in No. 2, and is barren in the former but productive in the latter. The dip in the strata (if the anticline affecting the oil sands passes south of well No. 2) might account for the difference in depth of the oil sand in the two wells, but it alone would hardly account for the difference in saturation of the sands. It is quite possible that the fault (which theoretically emerges somewhere near Hill well No. 4) passes downward at such an angle as to cut the oil sand between Hill wells Nos. 2 and 3, throws the sand down on the north, and, while acting as an outlet for the oil in the sand for some distance on its northern or upper side, effectively seals up the truncated end of the same sand on its southern or lower side. This hypothesis assumes a downthrow on the north, a condition exactly opposite to that shown at the surface in Cebada Canyon. Alternate upthrow and downthrow on the same side of a single fault occurring at different times are not unusual in the Coast Ranges, so that such an explanation is not only possible but probable. To conform to the prevailing conditions the downthrow must have been on the north in pre-Fernando and on the south in Fernando or post-Fernando time.

The logs of the Wise & Denigan wells indicate a more or less local anticline in the Monterey. Its axis passes near well No. 2 of this group, and probably extends in an east-west direction parallel to the major lines of structure in the hills immediately to the north. This occurrence suggests the probable gentle folding of the Monterey in the region south of the Purisima Hills, in a manner similar to that which takes place under Burton Mesa farther west.

GEOLOGY.

GENERAL STATEMENT.

All the productive wells in the Lompoc field start in the Fernando formation and penetrate its clays, sandstones, and conglomerates for distances ranging from 45 to 800 feet. The great variation in the thickness of the Fernando in adjacent wells (the beds over much of the territory being nearly horizontal, implies great inequalities in the surface of the underlying Monterey shale, and this in turn signifies a profound unconformity between the two formations. Water is encountered in the Fernando at various depths in the different wells.

From the base of the Fernando to the top of the oil sand the wells pass through shale (largely "brown," according to the logs). Hard siliceous "shell" layers are encountered here and there in this shale, and in one well hard limy "shells" were struck at only 1,180 feet from the surface. These limy layers are abundant in the formation just above the oil zone, but are not found in most of the wells above this horizon.

Oil and gas are found in minor quantities in the shale at various depths, from 500 feet down in some of the wells in the northern part of the developed area, although such occurrences are not recorded for the wells in the southern part.

BURNT SHALE.

One of the most interesting features of the geology of the Monterey shale in this area is the evidence that combustion has taken place within it at certain points about 1,000 feet below the surface. Mr. Orcutt, of the Union Oil Company, exhibited samples of red shale coming from depths of 950 and 1,040 feet below the surface in Hill well No. 1, which are identical in appearance and texture to the burnt shale found so abundantly in the bituminous areas of the Monterey on the north side of the Santa Maria field and in other fields throughout the State. Traces of petroleum were associated with the upper stratum of burnt shale in Hill well No. 1.

OIL ZONES.

The principal productive oil zone in the Lompoc field is struck at depths below the surface ranging from about 2,200 to more than 4,100 feet. In nearly all the wells the productive strata are overlain by a more or less prominent series of limy "shell" layers, which apparently act as barriers to the upward migration of the oil at the present time. The beds beneath these limy "shells" are true sands in most places, although in some of the wells these sands are interstratified with varying quantities of shale and limestone "shells." The thickness of the oil zone varies from about 160 to 700 feet, and a productive series of sands, shales, and "shells" is said to be penetrated for a

distance of 1,100 feet in one well. Either water sand, dry oil sand, or limy "shell" usually defines the base of the productive zone.

THE OIL.

Two grades of oil are struck in this field, one a black oil with a gravity of 18° to 24°, the other a brown to greenish oil of about 35° Baumé. The black oil is produced by most of the wells, the lighter variety coming only from the Logan well of the Los Alamos Oil and Development Company and the No. 3 Wise & Denigan well of the Union Oil Company. The relations of occurrence of the two grades are not known. One of the wells yields an emulsion of water and 20° oil, which is reddish brown in color as it comes from the well. This oil turns to the usual black color on separation of the water by settling.

PRODUCTION.

The production of the individual wells ranges from 100 to 1,000 barrels per day, the best producers averaging from 300 to 500 barrels. One of the wells which gave an initial output of 200 to 300 barrels at first, suddenly began flowing 1,000 barrels per day. This continued for a few days and then gradually fell off to 300 barrels, which it is still yielding. It is said that the wells, as a rule, are exceptionally steady producers, falling off but little in the two years since the field was first opened. Very few of the wells have been tried to their full capacity, so that it is probable that yields greater than those mentioned will be recorded when the field is fully tested.

ARROYO GRANDE FIELD.

LOCATION.

Drilling has recently shown that at least certain portions of the region north and northwest of Arroyo Grande, in the San Luis quadrangle, San Luis Obispo County, a short distance north of the area shown on Pl. I, are underlain by productive oil formations. The successful wells belong to the Tiber Oil Company, and are located on the west side of Price Canyon about 3 miles northeast of Pismo and 7 miles slightly east of south of San Luis Obispo. Although outside of the immediate area covered by this report the occurrence is so important in showing an extension of the Santa Maria district toward the northwest as to merit mention here.

GEOLOGY.

The geology of the San Luis quadrangle has been mapped and described by H. W. Fairbanks in the San Luis folio.[a] According to

[a] Copies of this folio, which is No. 101 in the series making up the Geologic Atlas of the United States, should be in the hands of every oil man or other person interested in the natural resources of this region; it may be obtained for 25 cents from the Director of the United States Geological Survey, Washington, D. C.

this work nearly all of the territory of the hills between San Luis Obispo Creek and the Arroyo Grande Valley, with the exception of a rather small area of Monterey volcanic ash, shale, and diatomaceous earth north of Pismo, is covered by the Pismo formation. This formation is composed of sandstone, some of which is asphaltic, and cherty diatomaceous beds, and is the equivalent of the lower part of the Fernando formation as described for the hills adjacent to the south side of the Santa Maria Valley. The Pismo is unconformably underlain by the Monterey shale, which outcrops on either side of it.

STRUCTURE.

According to Fairbanks, the Pismo area forms a low syncline, striking northwest and southeast, its flanks resting against the upturned Monterey.

OCCURRENCE OF THE OIL.

The oil is derived from a great thickness of productive sands which probably represent the base of the Pismo and which rest upon the upturned and more or less contorted shale of the Monterey. Its occurrence in beds occupying a synclinal position is worthy of note, as ordinarily synclines are not highly productive. The Monterey is the oil-bearing formation in the Santa Maria district, and it is the ultimate source of the oil in this field also. The migration of the oil probably took place along joint cracks in the shale, as was the case with the asphaltum in the Santa Maria and other fields. The oil, on reaching the upper limit of the shale passed across the plane of unconformity and accumulated beneath an impervious shale in the porous sands at the base of the Pismo. Where this porous layer approaches the surface the more volatile parts of the oil have escaped and there remains nothing but the bitumen, while the more deeply covered sands retain the oil in its lighter and liquid state. The migration of the oil, as in every similar case coming under the notice of the writers, has been accompanied by a loss of its volatile constituents and a consequent lowering of the gravity. This is evidenced by the fact that although the gravity of the oil from the Monterey formation in the Santa Maria field averages about 25°, that from the Pismo in the Arroyo Grande field is only 14°.

CONCLUSIONS REGARDING FUTURE DEVELOPMENT.

It seems almost certain that considerable portions of the Pismo formation toward the middle of the area northwest and north of Arroyo Grande will be found to be oil producing. This conclusion is based on the assumption that the Pismo of this region is underlain

by the oil-yielding Monterey. The surface evidence of such a condition is most conclusive. What effect local flexures either in the Monterey below the Pismo or in the Pismo itself will have on the production, only drilling will determine. According to Fairbanks's interpretation of the structure of the area, the depth at which the oil will be struck ought to decrease from the middle of the area toward both the northeast and southwest. The only well fully tested in the region yields 500 barrels of 14° oil per day, so that the prospects for the development of a good field are unusually bright.

As the Monterey shale underlying the Pismo of the Arroyo Grande field is continuous with the Monterey mapped in the Lompoc quadrangle northeast of the Santa Maria Valley, it is reasonable to suppose that there are considerable portions of this great belt of Monterey that will prove productive. The local structure is usually the determining factor in the accumulation of the petroleum, so that a thorough knowledge of this is essential to economical test drilling.

HUASNA FIELD.

The Huasna field lies east of the Arroyo Grande field and north of the Lompoc quadrangle. Prospect drilling is now going on in this region, but with what results the writers are not able to say. During a very hasty trip through this region in the summer of 1905 the senior writer noted great areas of Monterey shale, with some interbedded coarse granitic sandstones, in many places of considerable thickness. Such conditions are ideal for the accumulation of petroleum if the beds are not too sharply folded. This Monterey area is probably the continuation of that exposed in the northeastern part of the Lompoc quadrangle, and may connect the latter with the Monterey area east of Arroyo Grande and also with that covering the summit of the Santa Lucia Range a few miles east of San Luis Obispo. It is to be regretted that no maps adequate for showing the structure of the formations in the region east of the San Luis quadrangle and north of the Lompoc quadrangle are available. Without these it will be impossible to do for this region such detailed geologic and structural mapping as has already been done for the two quadrangles mentioned.

OIL OF THE SANTA MARIA DISTRICT.

ORIGIN.

There is no doubt that the petroleum in the Santa Maria district is indigenous to the Monterey shale. Bitumen is a characteristic part of that formation throughout its wide extent over an area covering hundreds of square miles, and there is no other formation

but the Eocene shales in which it is characteristic, or in which it occurs in appreciable quantity except locally, although there are numerous formations which would be capable of storing oil if any had originated in them. Moreover, the bituminous Monterey shale of the Coast Ranges does not occur consistently above or below any one formation from which the oil could have been derived. It lies unconformably upon ancient metamorphic rocks; granite and other igneous rocks; Jurassic, Cretaceous, or early Tertiary sediments; or conformably over lower Miocene beds, according to local conditions; and it is either not covered by later deposits or is buried by sediments of various ages, in different places.

The decision is therefore unavoidable that some ingredients of the Monterey shale gave rise to the oil, and the question arises what these were. The organic composition of the strata making up this formation is discussed on pages 38–43, where a number of animal and plant forms that may have contributed to the oil are enumerated. The writers are strongly of the belief that the petroleum was derived largely from the minute organisms, especially the plant organisms (diatoms), which are present in such abundance in these shales. The chemists Peckham and Clarke believe that the nitrogen present in the California oil proves its origin from animal substance. But it is not necessary to consider that this petroleum originated entirely from either animal or vegetable matter; it is more probably the product of remains of both kinds combined, much of the nitrogenous material being furnished by animal tissue.

Other small organisms of a low order present in the Monterey shale besides the diatoms are Foraminifera and Radiolaria, both orders of marine animals. They became embedded in the mass of the organic and adventitious silt material of the deposit at the sea bottom, and their bodies were thus preserved with the hard parts and may have become a source of hydrocarbons and nitrogen for the petroleum. The fact that the limestone and calcareous shale of the Monterey are usually very bituminous suggests the conclusion that the Foraminifera were great oil formers, inasmuch as these rocks are thought to be made up largely of foraminiferal remains, although of course the calcareous strata may owe their petroliferous character to their porosity. In many places the body of the limestone is full of minute specks of oil contained in cavities about the size of the interior of foraminiferal skeletons, and these specks give the impression that the oil is not far from its point of origin. Albert Mann, of the United States Department of Agriculture, makes the suggestion that possibly Foraminifera originally made up a greater part of the shales than now appears and that their easily destroyed calcareous tests were leached out, the soft parts adding their quota to the total amount of petroleum formed and owing to their animal character helping to

cause the relatively high percentage of nitrogen found in the California oils.

Fish skeletons are sometimes found in the shale, and flat impressions, large and small, that appear to be the scales of fish are abundant and very characteristic of certain portions of this formation, seeming to show that fish remains were in sufficient abundance to add at least something to the oil and to supply a portion of the nitrogen. On the other hand, these fossilized parts may have been originally separated from the tissue before they dropped to the ocean bottom or before being buried in the deposit, as by far the greater number of fish are believed to die violent deaths and to serve as food for larger fish or other animals.

Other animal organisms which were present and which may have contributed hydrocarbons and nitrogen were sponges, mollusks, and crustaceans—such as crabs and possibly ostracods. The impressions of seaweed occur in the shale but sparingly, probably because plants of this kind are restricted in habitat to shallower water than that in which it is believed the greater part of the Monterey was laid down, so that it is not probable that these plants have been large contributors to the material of the oil.

It is certain that there was a sufficiency of organic material included with the Monterey deposits to give rise to a vast quantity of petroleum, as is proved by a rough estimate based on low calculations of the amount of such material present. If the area covered by the Monterey formation in the Santa Maria district, including territory surely covered by it whether the formation now outcrops there or not, be taken as 800 square miles and the thickness of the formation as half a mile, the total volume of the deposit would be 400 cubic miles. These figures are low, especially in view of the fact that the average thickness and the areal extent of the formation were much greater when the oil began to be accumulated than at present. If we regard for the moment the diatoms alone to be the source of the oil, and only 1 per cent of the formation to be made up of these organisms, there would be 4 cubic miles of diatoms; and if we suppose further, simply as a rough guess, that these forms gave rise to an amount of petroleum equaling 1 per cent of their volume, we would have 1,000,000,000 barrels of oil as the amount distilled within the Monterey in this district, or more than thirty-three times the total production of oil in California for 1904, or eight times the production in the United States for the same year. According to Albert Mann, who has recently made an extensive study of diatoms, these plants when living secrete algal wax or oil in amounts varying from 0.75 per cent to as much as 4 per cent of their total volume. The amount of petroleum that might be derived from the diatoms is entirely unknown; but if the figure assumed hypothetically as

being 1 per cent is too liberal, it would seem that the low estimates of the amount of diatomaceous material present and the complete ignoring of the other important organic sources for oil in the shale, would still cause the estimate to be conservative.

In considering the question, What kind of organic material has a character most favorable for producing oil? the relative rate of putrefaction is important. Plants have the advantage in respect to their slower rate of decomposition. David White inclines to the view that plants are more favorable to the production of oil, largely for this reason. He says that putrefaction, which is largely a bacterial process, goes on more rapidly in animal tissue, while vegetable material has a tendency to turn into hydrocarbons. The slow decomposition of the protoplasm contents of the diatom frustule is especially significant. F. J. Keeley, of the Philadelphia Academy of Natural Sciences, says as follows in a letter:

> The only point I can think of that might have any bearing on the question of the relation of diatoms to petroleum is the fact that the organic matter of diatoms does not appear to decompose and become dissipated quickly after death, as is the case with most low organisms. It is well known that diatoms kept in water will show the shrunken contents for years, and Ehrenberg noted the presence of such organic contents in old fossil diatoms from Hanover, while J. Brun reports a similar observation in a fossil deposit from Holland.

It is worthy of note that many of the round white diatom tests of the soft Monterey shale contain minute specks of black that appear like bituminous material derived in situ from the diatom. These specks, however, are present in but a small proportion of the tests and there is no proof that the black substance has not come from infiltration and deposition in the slight hollow of the shell. Thin sections of the shale reveal small black filaments that appear to be carbonaceous material.

It is probable that the ooze at the sea bottom in Monterey time was being deposited very rapidly. The idea of rapid accumulation of the deposits of diatoms, aided by the accession of organic and detrital material of other kinds, is quite in keeping with the well-known faculty of these organisms for quick and abundant reproduction; and it is not only in keeping with but an essential corollary of the fact that deposits of such vast thickness were formed during middle Miocene time. This rapid accumulation created further favorable conditions for the production of oil, inasmuch as the organic substance that reached the sea floor became quickly buried without sufficient time intervening for decomposition to go very far. Thus the contents of the diatom frustules and all the other plant and animal remains became included in the body of the deposit.

The alkalinity of the shale may have been another favoring factor. As the deposits grew, salts of the sea water were probably included

in the porous mass and they may have acted as preservatives of the organisms to some extent.

As regards the age of the oil, it is stated by F. W. Clarke[a] that the process of formation of the oil from organic sources may not be slow, but, on the other hand, comparatively rapid. It is usually thought, however, that the process of distillation is slow and is continued during a long time. The petroleum in the Monterey may have been formed immediately after the deposit was laid down, or the production of it may be still in progress. There is evidence, however, in the presence of burnt shale in a Pleistocene deposit (see p. 52), in the old and eroded deposits of asphalt, and in the presence in certain asphalt deposits of the bones of extinct Pleistocene mammals[b] which were caught in tar springs in Pleistocene time, that much of the oil at least was formed in the Monterey and disseminated to the surface a long time ago. The accumulation and dissemination of the oil has probably gone on continuously ever since its first formation, the two processes taking place simultaneously. There may be portions of the formation from which the hydrocarbon content has not yet been extracted in the form of oil, whereas other portions may no longer contain any of the oil in its original disseminated condition. The metamorphism that gave rise to the harder shales may have had the effect of driving out the oil more completely than it has been separated from the softer shale, and thus aided its accumulation, although this is conjectural.

The general conclusion is that in the Santa Maria district the organic material in the Monterey shale that may have acted as the source of the oil was without a doubt adequate in amount for the production of the vast quantity of petroleum now present, and that the forms included in greatest abundance, the diatoms, were the chief source, although animals and perhaps other plants also contributed largely.

PHYSICAL PROPERTIES.

GENERAL STATEMENT.

The Santa Maria district yields four distinct grades of petroleum, in addition to the heavy oil which flows from springs or collects as asphalt deposits. These petroleums vary widely in their physical and chemical properties and as a consequence are utilized in many different ways, the lighter oils usually for refining, the heavier for fuel, road dressing, etc.

The oil as it comes from the wells contains varying quantities of gas, often amounting to a considerable percentage. The two prod-

[a] The data of geochemistry (in preparation for publication by the United States Geological Survey).
[b] Bull. U. S. Geol. Survey No. 309, 1907, pp. 154–155.

ucts are usually separated at the wells, the gas being utilized for heat or directly for power and the oil being run into tanks. This tank oil still contains gas, most of which, however, gradually passes off on exposure to the air, with a consequent lowering of the gravity of the oil. Before transportation by steamer it is necessary to pass the oil through a partial refining process for the removal of the lighter, volatile, more dangerous constituents; this is done at present in the refineries at Port Harford and Gaviota.

COLOR AND ODOR.

Nearly all of the oil in the Santa Maria district is dark brown in color. The exceptions are the black oil from the Arroyo Grande field, the reddish emulsion from one of the wells in the Hartnell-Brookshire area, and the brown to greenish oil found in certain of the wells in the Lompoc field. The heavier oil is the darker; the lighter grades show the greenish hues. The darkest oil in the Santa Maria field proper is the 19° petroleum from the wells in the eastern Western Union group. Some very dark oil is also said to come from the Lompoc field.

The heavy oil gives off an aroma not unlike some grades of lubricating oil, and, doubtless owing to the absence of hydrogen sulphide in solution, has little of the disagreeable odor common to that from some of the other California districts. In this district the lighter the oil, as a rule, the sharper and less agreeable is its odor.

GRAVITY.

The gravity of the oil ranges from 14° to about 35° Baumé. The heaviest oil (14°) comes from the Arroyo Grande field; 18° to 24° oil from the Lompoc field; 19° oil from the eastern group of Western Union wells; 24° to 29° oil from the Santa Maria field; and 35° oil from the Los Alamos Oil and Development Company's well and one of the Wise & Denigan wells. The average gravity of the oil from the Santa Maria field proper is between 26° and 27°, thus putting it well into the class of valuable refinable petroleums.

VISCOSITY.

The relative viscosity of several of the oils from the Santa Maria district, together with similar data for other California oils, is shown in the table on page 116.

CHEMICAL PROPERTIES.

Few data concerning the chemical properties of the oil from the Santa Maria district are at present available for publication except

those found in Bulletins Nos. 31 and 32 of the California State Mining Bureau. The analyses of Santa Maria oil contained in these bulletins were made by H. N. Cooper, and, together with those of oils from some of the other California districts, are copied in the table below.

The only definite information concerning the ultimate composition of the oil is contained in a table by P. W. Prutzman[a] showing the incidental constituents of California crude oil. This author states that a Santa Maria oil of 17° (probably from the eastern group of Western Union wells) contained 0.43 per cent of nitrogen, no sulphur, and 8.37 per cent of asphaltene. The freedom of the Santa Maria oil from sulphur is one of its chief and valuable characteristics.

The following table[b] contains analyses of four oils from the Santa Maria district, accompanied by analyses of twelve other California oils for purposes of comparison. The oil of analysis No. 3 in the table is the most characteristic of the average product of the Santa Maria field.

Following the table are distillation tests.

Chemical analyses of California petroleum.

[By H. N. Cooper, chemist. Samples collected by Marion Aubury, field assistant.]

No. of analysis.	Name of company.	County.	District.	Gravity.	Specific gravity of crude at 15° C. (about 60° F.).
				° *B.*	
1	Western Union Oil Co.	Santa Barbara	Western Union	20	0.9337
2	do.	do.	Carreaga	34.6	.8508
3	Pinal Oil Co.	do.		27.6	.8882
4	Union Oil Co. of California	do.	Lompoc	16.2	.9574
5	Sea Cliff Oil Co.	do.	Summerland	14.9	.9665
6	King Refining Co.	Kern	Kern River field	13	.9792
7	I. W. Shirley	Los Angeles	Middle field	16.5	.9559
8	Southern Pacific Oil Co.	Kern	McKittrick	18.5	.9425
9	Home Oil Co.	Los Angeles	Whittier	20.7	.9291
10	Brea Canyon Oil Co.	Orange	Fullerton	23	.9147
11	Los Angeles Pacific Rwy. Co.	Ventura	Santa Paula	27.3	.8900
12	Union Oil Co. of California	do.	Adams Canyon	28.9	.8814
13	California Oilfields (Limited)	Fresno	Coalinga	31.3	.8680
14	Home Oil Co.	do.	do.	34.1	.8530
15	Los Angeles Pacific Rwy. Co.	Ventura	Timber Canyon	35.1	.8481
16	Pacific Coast Oil Co.	Los Angeles	Pico Canyon	37.3	.8367

[a] Bull. California State Mining Bureau No. 32, 1904, p. 224.

[b] For a detailed description of the methods used in obtaining the data recorded in this table the reader is referred to Bull. California State Mining Bureau No. 31, p. 1; idem, No. 32, 1904, table opp. p. 230; or to Bull. U. S. Geol. Survey No 309, 1907, pp. 205-208.

Chemical analyses of California petroleum—Continued.

No. of analysis.	Flash.	Viscosity. At 15° C. (about 60° F.). Seconds.	Viscosity. At 15° C. (about 60° F.). Seconds divided by 27½ or water=1.	Viscosity. At 85° C. (185° F.). Seconds.	Viscosity. At 85° C. (185° F.). Seconds divided by 27½ or water=1.	Sulphur.	Calorific value of dry samples.[a]	Calorific values per cubic centimeter.
	°					Per cent.		
1	Below 15	1,060	38.40	77½	2.81	2.08	10.369	9,907
2	15	47⅜	1.72	29⅜	1.07	.60	10,825	9,203
3	Below 15	90	3.27	37⅜	1.36	1.56	10,543	9,364
4	21	Over 1,800	Over 65.00	227	8.23	4.43	10,258	9,822
5	Above 70	Over 1,800	Over 65.00	108	3.91	.44	10,348	10,001
6	Above 70	Over 1,800	Over 65.00	410	14.86	....	....	....
7	Above 70	Over 1,800	Over 65.00	78	2.83	.85	10,437	9,976
8	32	1,100	39.85	54	1.96	.77	10,402	9,804
9	26	393	14.24	43	1.56	....	....	....
10	Below 15	264	9.56	41½	1.50	.94	10,581	9,678
11	Below 15	61⅜	2.23	34½	1.24	....	....	....
12	Below 15	162½	5.91	37	1.34	.48	10,647	9,384
13	Below 15	56	2.03	32½	1.18	.38	10,739	9,321
14	Below 15	28½	1.03	25½	.99	.06	10,598	9,040
15	Below 15	45⅗	1.66	31⅕	1.13	....	....	....
16	Below 15	38½	1.40	29½	1.07	.28	11,141	9,322

No. of analysis.	Distillation. Percentage. Water.	Up to 100° C.	100°-150° C.	150°-200° C.	200°-250° C.	250°-300° C.	300° C. to asphalt. A.	300° C. to asphalt. B.	Asphalt.	Loss or gain.
1	None.	0.9	6	10.5	9.3	11	39.5	....	22	−0.8
2	None.	8.6	16	12	13.4	10.8	23	7.4	8	− .8
3	None.	8.2	17.7	12.1	9.4	9.1	29.7	....	12	−1.8
4	7	1.3	3.9	5.5	7.7	18.3	34.3	....	20.6	−1.4
5	.7	0	0	1	10	17.4	45.5	....	23.5	−1.9
6	None.	0	0	0	0	22.5	37.5	6.9	31.1	−2
7	.8	0	0	0	7.6	13.9	40	14.5	21.8	−1.4
8	None.	0	4.2	8.9	8.7	20.2	27.5	7.5	22.5	− .5
9	None.	0	4.2	9.6	14	14.7	23	16.8	15.7	−2
10	None.	4.2	13.9	8.9	9.7	18.3	24.2	5	13.3	−2.5
11	None.	9.3	16.5	11.8	7.7	9.1	31.8	....	13	− .8
12	None.	4	14.1	9.1	9.3	10.1	43	....	9.8	− .6
13	None.	10.4	13.8	10.5	10.3	17.5	20.8	7.3	9.1	− .3
14	None.	5.5	30.6	21.5	25.4	8.1	5	....	4.1	+ .2
15	None.	15.3	15	9.5	9.9	9.9	28	....	10.6	−1.8
16	None.	10.5	20.4	13.8	13	11.1	16.9	6.8	6.8	− .7

No. of analysis.	Distillation. Gravity of preceding fractions at 15° C. (about 60° F.). Up to 100° C.	100°-150° C.	150°-200° C.	200°-250° C.	250°-300° C.	300° C. to asphalt. A.	300° C. to asphalt. B.
1	....	0.7596	0.8087	0.8538	0.8875	0.9167	....
2	0.7185	.7683	.8028	.8354	.8574	.8788	0.8822
3	.7123	.7617	.8132	.8583	.8899	.9085	....
4	....	.7737	.7906	.8316	.8613	.8992	....
5	....	....	....	.8516	.8840	.9347	....
6	....	....	....	....	.8901	.8997	.8938
7	....	....	....	.8625	.8849	.9021	.9053
8	....	.7700	.8235	.8427	.8976	.8982	.8985
9	....	.7756	.8313	.8672	.8991	.9210	.9166
10	.7252	.7701	.8172	.8597	.8937	.8955	.9062
11	.7228	.7724	.8202	.8613	.8901	.9154	....
12	.7250	.7736	.8111	.8388	.8547	.8778	....
13	.6906	.7630	.8041	.8382	.8774	.8866	.9062
14	.7395	.8074	.8396	.8919	.9227	.9374	....
15	.7002	.7639	.8015	.8321	.8624	.8875	....
16	.7472	.7659	.8040	.8359	.8606	.8870	.8720

[a] To convert calories into British thermal units, multiply by 1.8.

Proximate analysis of a Santa Maria oil.[a]

[Gravity, 16.9° Baumé.]

	Per cent.	Gravity (°B.).
DISTILLATION.		
Below 150° C	1.0	....
150° to 270° C	24.0	39.5
Above 270° C	31.1	....
Asphalt, grade D	41.9	....
Loss	2.0	....
CALCULATED ANALYSIS.		
Total gasoline	2.7	55
Kerosene	16.8	41
Middlings and lubricants	36.6	....
Asphalt, by volume[b]	41.9	....
Loss	2.0	....

[a] Prutzman, P. W., Bull. California State Mining Bureau, No. 32, 1904, Table 25.
[b] By weight (154 pounds per barrel), 46.2 per cent.

The following analyses of oils from the Santa Maria district have been kindly furnished by Prof. Edmond O'Neill, of the University of California, who writes concerning them as follows:

I do not know the exact locations of the wells from which these oils were derived, but they are from the first wells opened in the Santa Maria property [probably the Hartnell or the Santa Maria Oil and Gas Company lease]. There is very little difference in the character of oils from all this district, except in the proportion of light constituents and the corresponding percentage of sulphur. Most of these oils contain water, which seems to be either in a state of fine emulsion, or possibly in some feeble form of hydration—that is, frequently the water will not settle out on standing, even by centrifugalizing—nor will it all be driven off at a temperature of 100° Centigrade; but at a somewhat higher temperature it seems to be given off almost with explosive violence.

Analyses and tests of six samples of oil from wells near Santa Maria.

[Made by Edmond O'Neill.]

ANALYSES.

	No. 3.	No. 4.	No. 5.
Gravity at 15.5° C. (=60° F.)	0.891	0.894	0.893
Gravity in degrees Baumé	27.800	27.600	27.500
Flash point, open tester	(a)	(a)	(a)
Flash point, closed tester	(a)	(a)	(a)
Burning point, open tester	23° C.=73.4° F.	22° C.=71.6° F.	21° C.=70° F.
Gasoline precipitate (asphaltine, etc.) ..... per cent	0.6	0.3	0.8
Sulphur ..... do	1.57	1.59	1.56
Calorific value ..... calories	10,260	10,363	10,229
Calorific value ..... B.T.U.	18,468	18,653	18,415

	No. 6.	No. 7.	No. 13.
Gravity at 15.5° C. (= 60° F.)	0.897	0.908	0.926
Gravity in degrees Baumé	26.800	24.800	21.670
Flash point, open tester	(a)	(a)	(a)
Flash point, closed tester	(a)	(a)	(a)
Burning point, open tester	21° C.=68° F.	20° C.=68° F.	24° C.=75° F.
Gasoline precipitate (asphaltine, etc.) ..... per cent	0.7	1.6	3.0
Sulphur ..... do	1.61	2.09	1.8
Calorific value ..... calories	10,284	18,375	8,078
Calorific value ..... B.T.U.	18,512	18,676	14,541

[a] Under 15° C.=60° F.

Analyses and tests of six samples of oil from wells near Santa Maria—Continued.

RESULTS OF DISTILLATION.

	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 13.
Water, per cent by volume	1.2	0.2	Trace.	Trace.	Trace.	10.8
Benzines, boiling point under 150° C. (302° F.):						
Per cent	24.5	22.1	20.2	23.5	18.5	16.8
Gravity, Specific	.745	.740	.740	.752	.752	.742
Gravity, Baumé	60°	61.°2	61.°2	52°	52°	60.°8
Kerosene, boiling point 150° C.-250° C. (302° F.-482° F.):						
Per cent	21.5	20.5	21.5	18.7	18.5	22.1
Gravity, Specific	.8345	.821	.818	.823	.822	.843
Gravity, Baumé	39	41.8	42.5	41.4	41.4	37
Lubricants, boiling point 250° C.-350° C. (482° F.-662° F.):						
Per cent	19.0	22.8	19.2	20.0	25.5	17.2
Gravity, Specific	.905	.889	.898	.897	.895	.899
Gravity, Baumé	25.3	28.2	26.6	26.6	27	26.4
Lubricants, boiling point above 350° C. (666° F.):						
Per cent	23.0	22.7	20.3	25.5	22.5	16.2
Gravity, Specific	.917	.905	.924	.917	.903	.906
Gravity, Baumé	23.2	25.3	22	23.2	25.6	25
Asphaltum:						
Per cent	10.8	11.7	8.8	12.3	15.0	16.9

ASSOCIATED HYDROCARBONS.

NATURAL GAS.

Throughout the Santa Maria district wherever any oil has been found it is invariably accompanied by considerable quantities of natural gas; indeed, this form of hydrocarbon is somewhat more widely distributed than the oil, occurring in many places in the shale above the oil zones and in some wells which have yielded no petroleum. The pressure of the gas varies from zone to zone and from well to well. The greatest pressure so far recorded was in Hartnell well No. 1, where, according to Mr. Orcutt, it was over 400 pounds per square inch during the initial flow of oil and gas. Most of the gas is utilized for the generation of heat or of power direct in gas engines. Some of it is utilized for domestic purposes in the field and the immediate vicinity.

ASPHALT.

Great deposits of asphalt are associated with the petroleum-bearing and later formations over certain portions of the Santa Maria district. The asphalt (in the broader sense of the word) within the district occurs in several different ways—as veins penetrating the Monterey shale and later formations; as impregnations of the shale, sands, or gravels in or overlying the Monterey; and as more or less impure effusions at the surface. The more important deposits are in the hills northwest of Arroyo Grande; in the region of Asphaltum and La Zaca creeks, east of Sisquoc; in Graciosa Ridge; and in the vicinity of Redrock Mountain. These deposits have been described

in detail by George H. Eldridge,[a] and are mentioned at various places throughout this bulletin; further discussion of them is therefore unnecessary.

TECHNOLOGY OF PRODUCTION AND UTILIZATION.

OIL COMPANIES OF THE SANTA MARIA DISTRICT.

The following is a statement of the oil operations in the Santa Maria district, compiled from all data available up to January 1, 1907:

Oil companies and wells in Santa Maria district.

Company.	Field.	Oil wells.			
		Productive.	Abandoned.	Drilling.	Total.
Anglo-Californian Oil Syndicate	Lompoc			1	1
Associated Oil Co	Arroyo Grande			1	1
Barca Oil Co	Lompoc		1		1
Brookshire Oil Co	Santa Maria	4	[b]1	1	6
California Coast Oil Co	do		1		1
California Coast Oil Co. (Union Oil Co.)	do	3			3
California-Newlove Oil Co	Arroyo Grande			1	1
Casmalia Ranch Oil and Development Co	Santa Maria		1		1
Claremont Oil Co	do		[b]1	1	2
Coast Line Oil Co	Lompoc		1		1
Coblentz Oil Co	Santa Maria			1	1
Crown Oil Co	Arroyo Grande			1	1
Crystal Oil Co	do			1	1
Diamond Oil Co	Santa Maria				
Dome Oil Co	do	1		1	2
Graciosa Oil Co	do	6		2	8
Hall & Hall Oil Co	do	1		1	2
La Grande Oil Co	Arroyo Grande			1	1
Laguna Land Co	do			1	1
Lompoc Oil Developing Co	Lompoc				
Los Alamos Oil and Development Co	do	1	2		3
Las Flores Land and Oil Co	Santa Maria				
McNee Oil Co	Arroyo Grande			1	1
Meridian Oil Co	Santa Maria			1	1
National Oil and Transportation Co. (Associated Oil Co.).	do			1	1
New Huasna Oil Co	Arroyo Grande			1	1
Oak Park Oil Co	do			1	1
Pennsylvania Oil Co	Santa Maria		1	1	2
Perpetual Oil Co	Arroyo Grande			1	1
Pacific Oil and Transportation Co. (Associated Oil Co.).	Santa Maria		1		1
Palmer Oil Co	do	1			1
Pinal Oil Co	do	11		3	14
Radium Oil Co	do		1		1
Recruit Oil Co. (Escolle and Newhall)	do		2	2	4
Rice Ranch Oil Co	do	2		1	3
Santa Barbara Oil Co	Santa Ynez			1	1
Santa Lucia Oil Co	Arroyo Grande			1	1
Santa Maria Oil Co. (Union Oil Co.)	Santa Maria	1		2	3
Santa Maria Oil and Gas Co. (Union Oil Co.)	do	4	1	3	8
Santa Ynez Valley Development Co	Santa Ynez				
Southern Pacific Co	Santa Maria			1	1
Standard Oil Co. (pipe lines, storage, etc.)	do				
Stillwell Oil Co	do				
Syndicate Oil Co. (Union Oil Co.)	do			1	1
The Oil Co	do		1		1
Tiber Oil Co	Arroyo Grande	1		2	3
Todos Santos Oil Co	Lompoc		1		1
Traders' Union Oil Co	Santa Maria		1		1
Union Oil Co.:					
Burton lease	Lompoc			1	1
Eefson lease	do	2	1	1	4
Folsom lease	Santa Maria	5		3	8

[a] The asphalt and bituminous rock deposits of the United States: Twenty-second Ann. Rept. U. S. Geol. Survey, part 5, 1901, pp. 209–452, pls. 25–58, figs. 1–52.

[b] Water well.

Oil companies and wells in Santa Maria district—Continued.

Company.	Field.	Oil wells.			
		Productive.	Abandoned.	Drilling.	Total.
Union Oil Co.—Continued.					
Fox lease	Santa Maria	5		1	6
Hartnell lease	do	2	a1	1	4
Hill lease	Lompoc	2	1	1	4
Hobbs lease	Santa Maria	8		2	10
Newlove	do			5	5
Wise & Denigan	Lompoc	8			8
Waldorf well	Santa Maria		1		1
Western Union Oil Co	do	26	3	2	31
Yakima Oil Co. (Lucas) (Associated Oil Co.).	do		1		1
		94	25	55	174

WELL DRILLING.

The wells in the Santa Maria district are among the deepest oil producers in the world, one of them reaching a depth of over 4,400 feet. Except at three or four wells, where rotary drills have been used to penetrate the soft sands and shales near the surface, all of the drilling has been done with the standard rig. The casing used ranges in diameter from 12 to 16 inches at the top down to 4½ inches, and in some wells, it is believed, even smaller, at the bottom. The cost of the deeper wells runs in general from $12,000 to $20,000, but several of the deepest are said to have cost even more than the latter figure.

Owing to the close texture of the shale, it is usually possible to carry the hole down for a considerable distance below the casing without danger of caving. Wherever the wells penetrate the soft Fernando beds for any considerable distance much trouble is experienced, but otherwise the drilling in the field is said to be as a rule comparatively easy.

PRODUCTION.

The production of oil in the Santa Maria region has been increasing rapidly in the last four or five years, but the figures of actual production do not fully indicate the increase in the capacity of the district. Lack of storage capacity, inadequate transportation facilities, and the low price of crude petroleum are factors which have kept down the amount produced and marketed. Well drilling has been going on steadily ever since the field was opened, but only a few companies have pushed their production up to the limit for any length of time.

Nearly all of the oil so far produced in the district has come from the Santa Maria field. The production of the district, including the Santa Maria, Lompoc, and Arroyo Grande fields, for the last five years is as follows:

Production of crude petroleum in Santa Maria oil district, 1902—1906.[a]

[Barrels of 42 gallons each.]

1902	99,283
1903	178,140
1904	1,367,174
1905	2,565,966
1906	4,906,513
	9,117,076

The estimated maximum capacity of the district January 1, 1907, is 40,400 barrels per day.

STORAGE CAPACITY.

The storage facilities of the district consist of steel and wooden tanks and open earthern reservoirs. The reservoirs are located only in the field and are used only temporarily or in cases of emergency. The total storage capacity of the district, not including the open reservoirs, is 1,464,000 barrels.

TRANSPORTATION FACILITIES.

The oil from the Santa Maria district is distributed by means of pipe lines, tank cars, and some of it eventually by tank steamers. The principal pipe lines of the district are four connecting the field with Port Harford and one running from the Western Union wells to Gaviota. The rail lines available are the Southern Pacific at Gaviota, Casmalia, and Betteravia, and the Pacific Coast at Carreaga and Orcutt. Tank steamers of the Associated, Standard, and Union oil companies take the product from Port Harford or Gaviota.

The following is a summary of the principal pipe lines in the district:

Pipe lines in Santa Maria oil district.

Company.	From—	To—	Distance.
			Miles.
Coast Oil Transport Co	Graciosa wells	Oil Port	34
Graciosa Oil Co	Wells	Casmalia	8
Los Alamos Oil and Development Co	do	Carreaga	
Pacific Oil and Transportation Co	Orcutt	Gaviota	51
Pinal and Brookshire oil companies	Wells	Graciosa station	2
Do	do	Betteravia	7
Standard Oil Co	Orcutt	Port Harford	32
Do	Western Union wells	Orcutt	7
Do	Hall, Dome, Pinal, and Brookshire wells.	do	3
Standard Oil Co. (2 lines)	Pacific Coast Oil Co.'s tanks.	Port Harford	
Union Oil Co	Orcutt	do	32
Do	do	do	32
Do	Lompoc field	Orcutt	16
Do	Escolle and Santa Maria Oil and Gas Co.'s wells.	do	3
Do	Fox, Hobbs, Folsom, and other wells.	do	3
Do	Reservoirs Nos. 1, 2, and 3	do	4
Western Union Oil Co	Wells	Carreaga	4

[a] Compiled from data furnished by the different operating companies.

REFINERIES.

The principal refineries utilizing the oil from the Santa Maria district are as follows:

California Petroleum Refineries, Limited.—The refinery of this newly organized company is now in course of erection at Oil Port, south of Port Harford. It is said that the initial capacity of this refinery will be about 7,000 barrels per day, and that all the usual products will be refined.

Pacific Oil Transportation Company.—The refinery of this company is located at Gaviota, and consists of nine stills with a capacity of 1,050 barrels of crude oil per day. The principal products are illuminants and fuel residue.

Standard Oil Company.—The plant of this company is located at Point Richmond, Contra Costa County, and is said to consist of 19 stills with a capacity of 5,000 barrels of crude oil and 4,000 barrels re-run per day. The products are illuminants, lubricants, and coke.

Union Oil Company of California.—The main refinery of this company is located at Oleum, Contra Costa County, and consists of a number of stills capable of producing illuminants, distillate, and asphalt.

UTILIZATION OF THE OIL.

Most of the oil from the Santa Maria district is refined, the lighter products being used for illuminants and for the direct generation of power in gas engines, and the heavier products and unrefined heavy oil for fuel, lubricants, road dressing, etc. With the exception of a very small amount used locally, all the oil is sent out of the district, the greater part of the product at present, it is believed, going to the refineries near San Francisco. Contracts recently made in South America, Japan, and the Hawaiian Islands indicate that within a short time much of the product of the district will be exported.

RÉSUMÉ.

The Santa Maria oil district, comprising the Santa Maria, Lompoc, Arroyo Grande, and Huasna fields, occupies the central and northern portions of the Lompoc and Guadalupe quadrangles, northern Santa Barbara County; the southern part of the San Luis quadrangle, southern San Luis Obispo County, and a small part of the unmapped area between the Lompoc and San Luis quadrangles.

The larger part of the district is a basin region inclosed between two divisions of the Coast Ranges—the San Rafael and Santa Ynez mountains—and the Pacific Ocean. The formations in this basin have undergone less disturbance than in the mountains and the conditions in it are good for the accumulation of oil.

The formations involved in the geology of the district include the Franciscan (Jurassic?) sandstone, shale, glaucophane schist, jasper, and intruded serpentine; Knoxville (lower Cretaceous) conglomerate, sandstone, and shale; pre-Monterey (which may include both Cretaceous and older Tertiary) conglomerate, sandstone, and shale; Tejon (Eocene) sandstone, shale, and conglomerate; Vaqueros (lower Miocene) conglomerate, sandstone, and shale; Monterey (middle Miocene) diatomaceous and flinty shale, limestone, calcerous shale, and volcanic ash; Fernando (Miocene-Pliocene-Pleistocene) conglomerate, sandstone, and shale; and Quaternary gravel, sand, clay, and alluvium. The sedimentary formations of Tertiary and early Quaternary age have a combined maximum thickness of at least 13,200 feet.

A variety of igneous rocks of Cretaceous and Tertiary age, mostly intrusive, outcrop over small areas.

The Monterey shale (middle Miocene) is the original and chief oil-bearing formation, the petroleum having originated and remained in it in large quantities. Some has escaped by seepage and collected in the overlying Fernando formation or the Quaternary terrace deposits, or has been dissipated. The oil is supposed to accumulate in fractured zones and porous sands in the lower portion of the Monterey, where brittle shale predominates, anticlines furnishing the most favorable conditions for accumulation. The Monterey shale is in large part of organic origin, being especially rich in diatoms, and the oil is supposed to be a product of the plant and animal remains inclosed in it. The quantity of these remains originally deposited with this formation is sufficient to account for a vast amount of derived oil.

Two structural systems prevail in the district, the features in the northeastern portion striking northwest and southeast, those in the southern portion striking east and west, and those in the intervening region trending in a direction intermediate between the two. Few faults of importance were noted in the field. The productive territory lies in a region of more or less gentle folds in the central part of the area, most of the wells being located along or near anticlines.

The wells range in depth from 1,500 to more than 4,000 feet. In the Santa Maria and Lompoc fields they obtain oil from zones of fractured shale, and possibly in certain places from sandy layers in the lower portion of the Monterey formation. The production of the individual wells ranges from 5 to 3,000 barrels per day, the average being between 300 and 400 barrels. The oil ranges in gravity from 19° to 35° Baumé, the greater part of it being about 25° to 27°. In the Arroyo Grande field the oil comes from sandstone at the base of the Fernando and is of 14° gravity. There is in all these fields much undeveloped territory which offers great promise of being

highly productive. The conditions affecting the presence of oil have been discussed for individual areas and those places enumerated in which the conditions seem favorable for its accumulation.

There are 52 oil companies interested in the district; 11 of these own all the producing wells. Of the 174 wells in the district 94 are productive, 55 are drilling, and 25 are abandoned. The total production of the field up to January 1, 1907, was 9,117,076 barrels; the production for 1906 alone was 4,906,513 barrels.

PLATES XII TO XXVI.

PLATE XII.

TEJON (EOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.)

FIG. 1. *Cardium breweri* Gabb. Type. Right valve; altitude 61 mm. View of exterior. Pal. California, vol. 1, 1869, pl. 24, fig. 155. A common species in the Eocene of the Santa Ynez Mountains.

FIG. 2*a*. *Crassatellites collina* Conrad. U.S.N.M. 165312. Left valve; longitude 87 mm. View of exterior. San Julian ranch (4507). Characteristic of this horizon.

FIG. 2*b*. View of anterior end of same specimen.

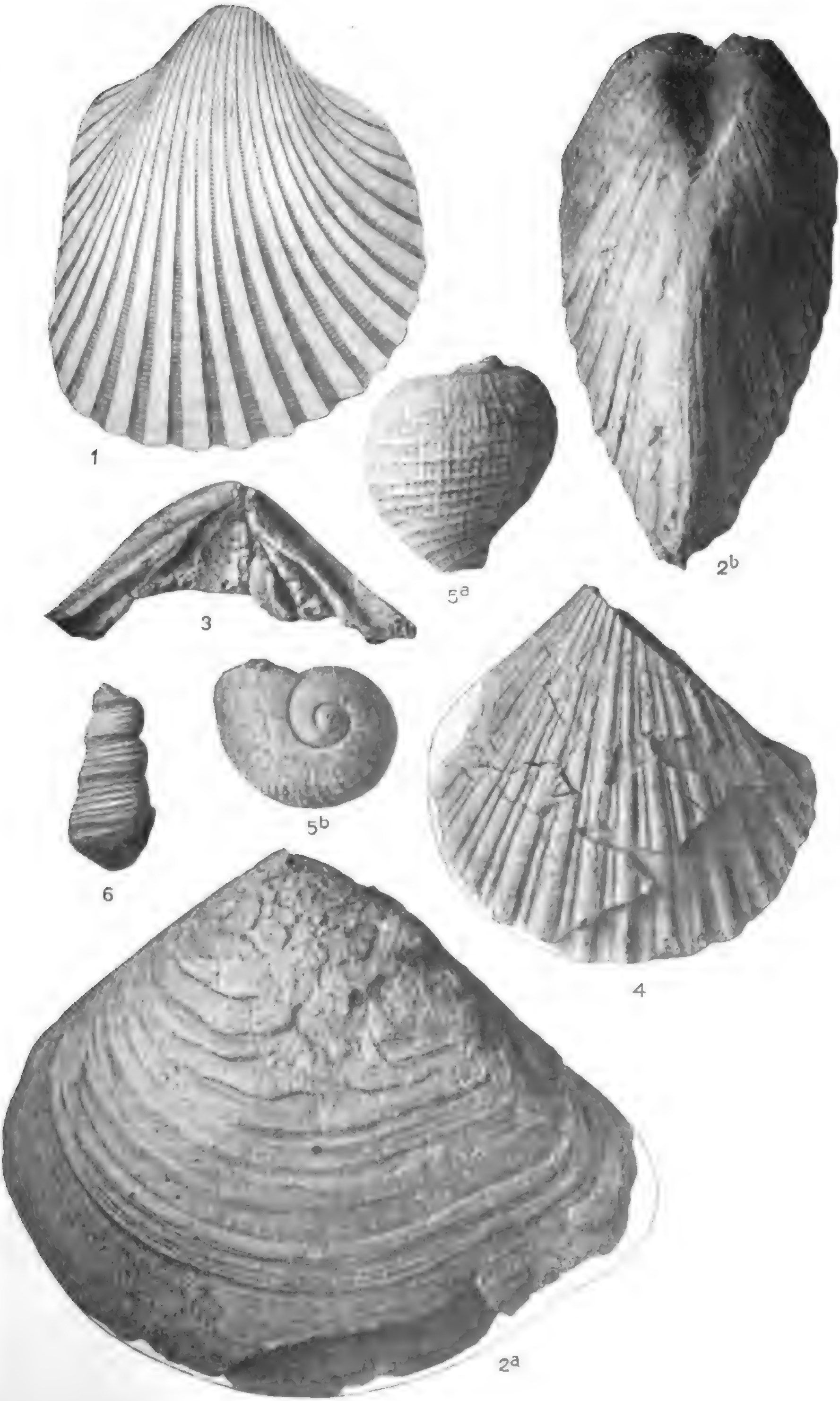
FIG. 3. *Crassstellites collina* Conrad. U.S.N.M. 165312. Hinge. Same locality as fig. 2.

FIG. 4. *Pecten* (*Chlamys*) *yneziana* Arnold. U.S.N.M. 165313. Paratype. Altitude 52 mm. View of exterior. San Julian ranch (4507). Characteristic of this horizon.

FIG. 5*a*. *Ficus mamillatus* Gabb. U.S.N.M. 165319. Altitude 31 mm. View of back. North of Sudden (4518). Characteristic of this horizon.

FIG. 5*b*. View of top of same specimen.

FIG. 6. *Turritella uvasana* Conrad. U.S.N.M. 165327. Altitude of imperfect specimen 25 mm. Aperture view. North of Sudden (4578). Characteristic of this horizon.



TEJON (EOCENE) FOSSILS.

PLATE XIII.

KNOXVILLE (CRETACEOUS) AND TEJON (EOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.)

FIG. 1. *Aucella piochii* Gabb. U.S.N.M. 30831. Right valve; altitude 25 mm. View of exterior. Knoxville (lower Cretaceous) formation, East Fork Tepusquet Creek (4173). Characteristic of the lower Cretaceous throughout the Coast Ranges.

FIG. 2. *Aucella piochii* Gabb. U.S.N.M. 30831. Left valve; altitude 15 mm. View of exterior, × 2. Same locality and horizon as fig. 1.

FIG. 3*a*. *Aucella piochii* Gabb. Left valve; altitude 27 mm. View of exterior. Bull. U. S. Geol. Survey No. 133, 1895, pl. 4, fig. 6.

FIG. 3*b*. Exterior of right valve of same specimen. Op. cit., pl. 4, fig. 7.

FIG. 4. *Venericardia planicosta* Lamarck, U.S.N.M. 164973. Left valve; longitude 84 mm. Eocene, Little Falls, Wash. This is the most widespread and characteristic Eocene species in the world.

FIG. 5*a*. *Turritella* (*martinezensis* Gabb) var. *? lompocensis* Arnold. Paratype. Altitude of fragment, 30 mm. Back view. Same locality as fig. 8.

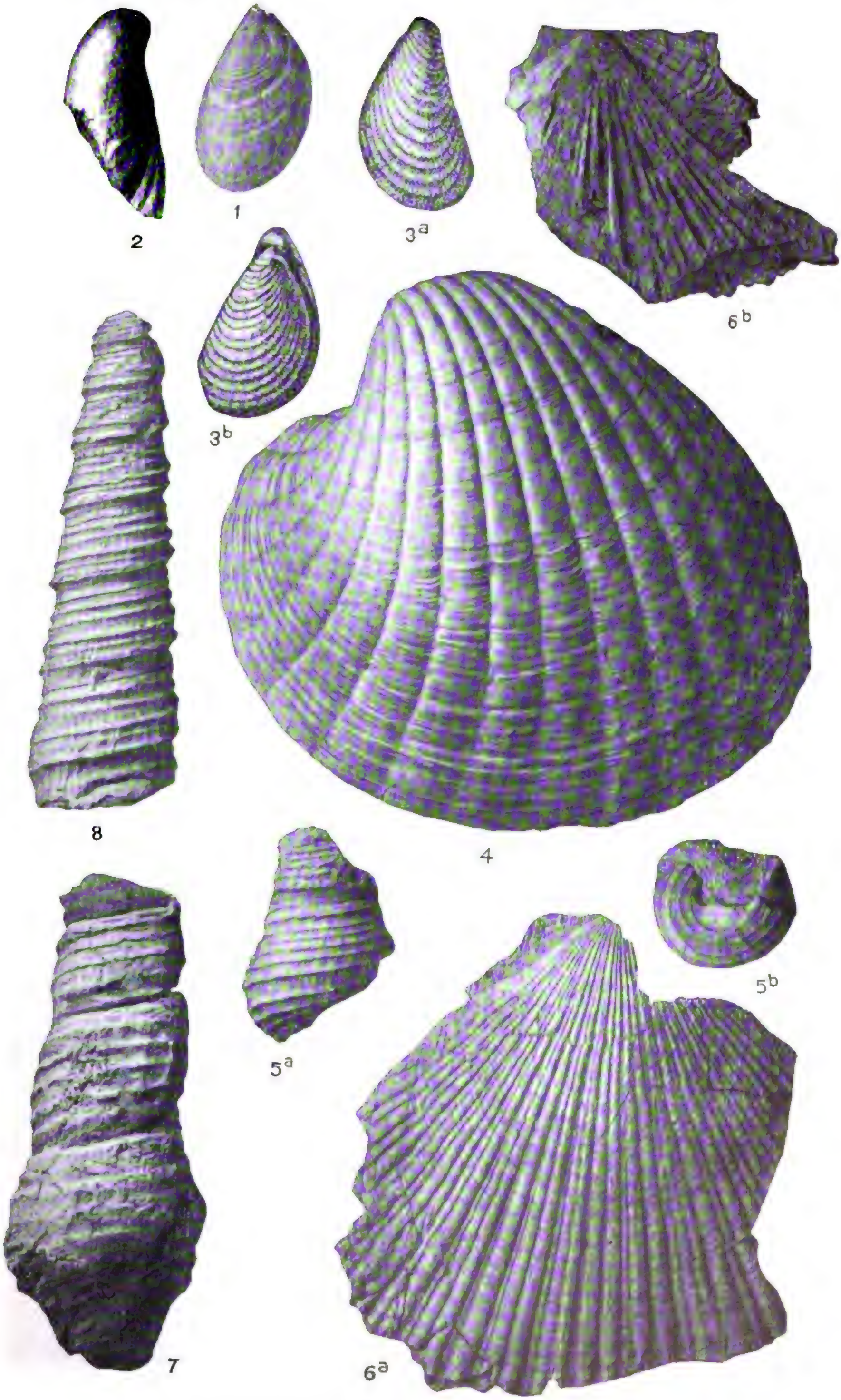
FIG. 5*b*. Basal view of same specimen.

FIG. 6*a*. *Pecten* (*Chlamys*) *yneziana* Arnold. U.S.N.M. 165313. Type. Right valve; altitude 64 mm. View of exterior. San Julian ranch (4507). Characteristic of this horizon.

FIG. 6*b*. Same species. Length of hinge of right valve 25 mm.

FIG. 7. *Turritella uvasana* Conrad. U.S.N.M. 165326. Altitude of imperfect specimen 68 mm. Aperture view. San Julian ranch (4507). Characteristic of the Eocene throughout the Coast Ranges.

FIG. 8. *Turritella* (*martinezensis* Gabb) var. *? lompocensis* Arnold. U.S.N.M. 165316. Type. Longitude 68 mm. View of back. Southwest of Lompoc (4509).



KNOXVILLE (CRETACEOUS) AND TEJON (EOCENE) FOSSILS

PLATE XIV.

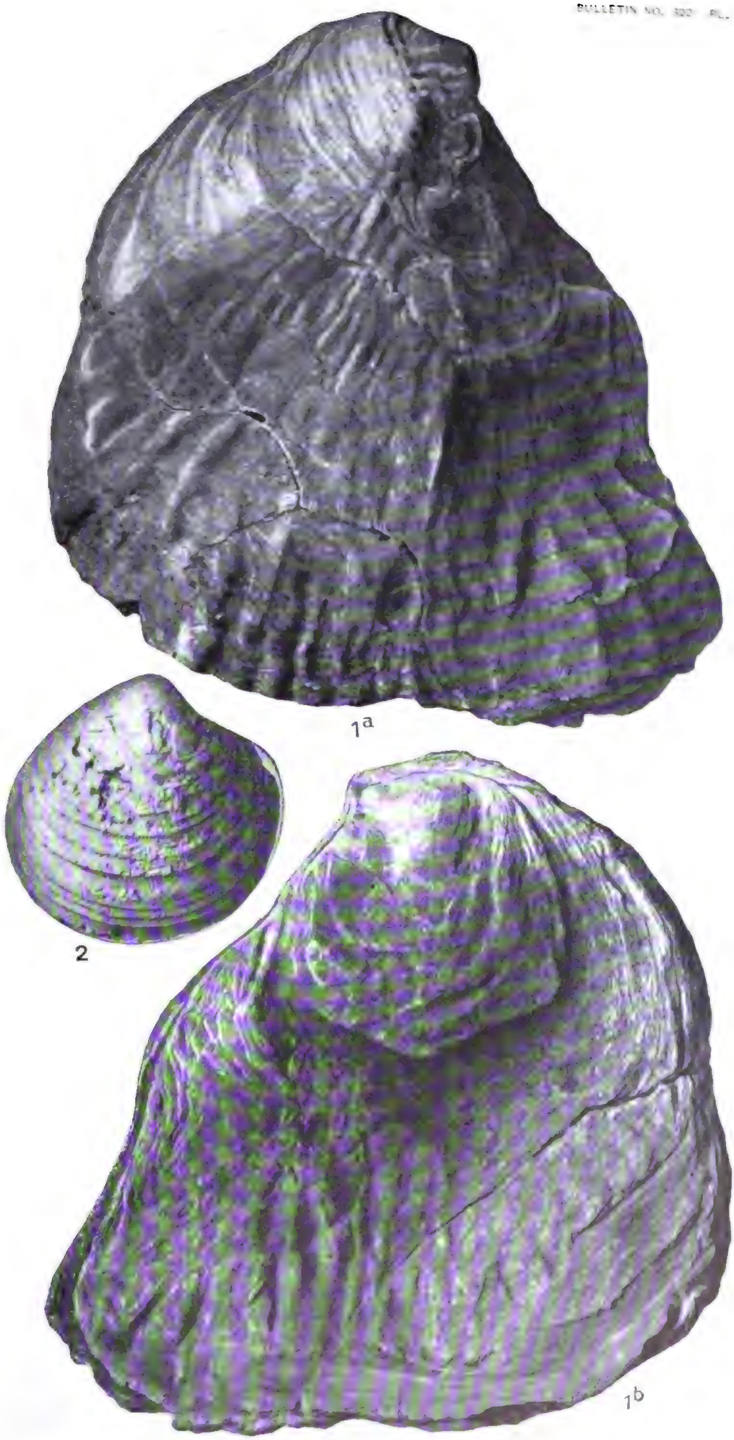
TEJON (EOCENE) PELECYPODA.

(Unless otherwise indicated all figures are natural size.)

FIG. 1*a*. *Ostrea idriaensis* Gabb. U.S.N.M. 165318. Left valve; altitude 114 mm. View of exterior. North of Sudden (4518). Characteristic of this horizon.

FIG. 1*b*. View of exterior of right valve of same specimen.

FIG. 2. *Phacoides cumulata* Gabb. U.S.N.M. 165328. Right valve; altitude 10 mm. View of exterior, × 4. Three miles north of Sudden (4518); also known from type locality of Tejon formation.



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TEJON (EOCENE) PELECYPODA.

PLATE XV.

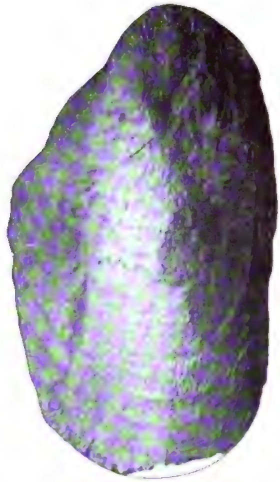
VAQUEROS (LOWER MIOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.)

FIG. 1*a*. *Purpura vaquerosensis* Arnold. Collection of Delos Arnold. Type. Altitude 100 mm Aperture view. Lynchs Mountain, Monterey County, Cal.

FIG. 1*b*. Back view of same specimen.

FIG. 2. *Modiolus ynezianu* Arnold. U.S.N.M. 165324. Type. Right valve; altitude 31 mm. View of exterior, × 2. San Julian ranch (4504). Characteristic of this horizon.



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1a

1b

VAQUEROS (LOWER MIOCENE) FOSSILS

PLATE XVI.

VAQUEROS (LOWER MIOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.)

FIG. 1. *Pecten (Lyropecten) magnolia* Conrad. U.S.N.M. 165317. Right valve; altitude 155 mm. View of exterior, × ½. San Julian ranch. A characteristic Vaqueros species.

FIG. 2. *Ostrea eldridgei* Arnold. U.S.N.M. 165307. Left valve; altitude 100 mm. View of exterior. Mouth of Ballard Canyon, 2 miles south of Santa Ynez (4478). Characteristic of this horizon.

FIG. 3. *Turritella inezíana* Conrad. U.S.N.M. 165321. Altitude 120 mm. View of side. Ten miles west of Santa Ynez (4514). Characteristic of this horizon throughout the Coast Ranges.

VAQUEROS (LOWER MIOCENE) FOSSILS.

PLATE XVII.

Vaqueros (Lower Miocene) Pelecypoda and Brachiopoda.

(Unless otherwise indicated all figures are natural size.)

Fig. 1. *Pecten* (*Pecten*) *vanvlecki* Arnold. U.S.N.M. 165305. Type. Right valve; altitude 64 mm. View of exterior. Mouth of Ballard Canyon, 2 miles south of Santa Ynez (4478). Characteristic of this horizon.

Fig. 2. *Pecten* (*Pecten*) *vanvlecki* Arnold. U.S.N.M. 165306. Paratype. Left valve; altitude 72 mm. View of exterior. Mouth of Ballard Canyon, 2 miles south of Santa Ynez (4478). Characteristic of this horizon.

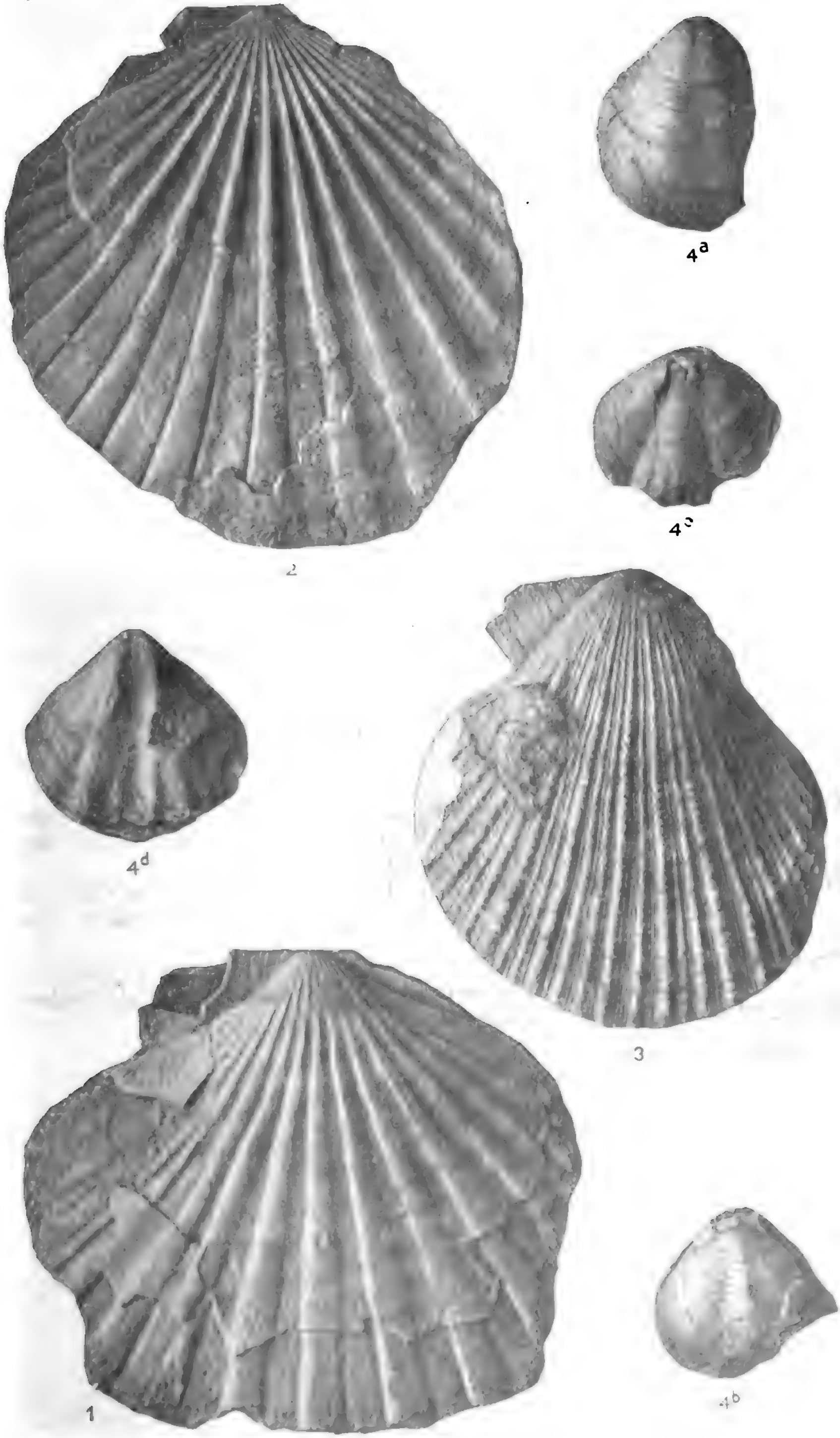
Fig. 3. *Pecten* (*Chlamys*) *sespeensis* var. *hydei* Arnold. U.S.N.M. 165308. Left valve; altitude 60 mm. View of exterior. Mouth of Ballard Canyon, 2 miles south of Santa Ynez (4478). Characteristic of this horizon.

Fig. 4*a*. *Terebratalia kennedyi* Dall. U.S.N.M. 165325. Type. Ventral valve; altitude 26 mm. View of exterior. Lime quarry 5 miles southwest of Lompoc (4521). Characteristic of this horizon.

Fig. 4*b*. Dorsal valve of same species; altitude of fragment 18 mm. View of exterior.

Fig. 4*c*. Dorsal valve of same species; altitude 19 mm. View of exterior.

Fig. 4*d*. Ventral valve of same species; altitude 28 mm. View of exterior.



VAQUEROS (LOWER MIOCENE) PELECYPODA AND BRACHIOPODA.

PLATE XVIII.

Vaqueros (Lower Miocene) Pelecypoda.

(Unless otherwise indicated all figures are one-half natural size.)

Fig. 1. *Pecten (Lyropecten) crassicardo* Conrad. U.S.N.M. 164967. Exterior of valve, showing characteristic sculpture; altitude 90 mm. Ojai Valley, Ventura County, Cal. This species ranges throughout the Miocene, being commoner in the lower part in southern California, in the upper part in central California.

Fig. 2. *Pecten (Amusium) lompocensis* Arnold. Collection of California Academy of Sciences. Holotype. Mold of interior of left valve; altitude 105 mm. Four miles south of Lompoc.

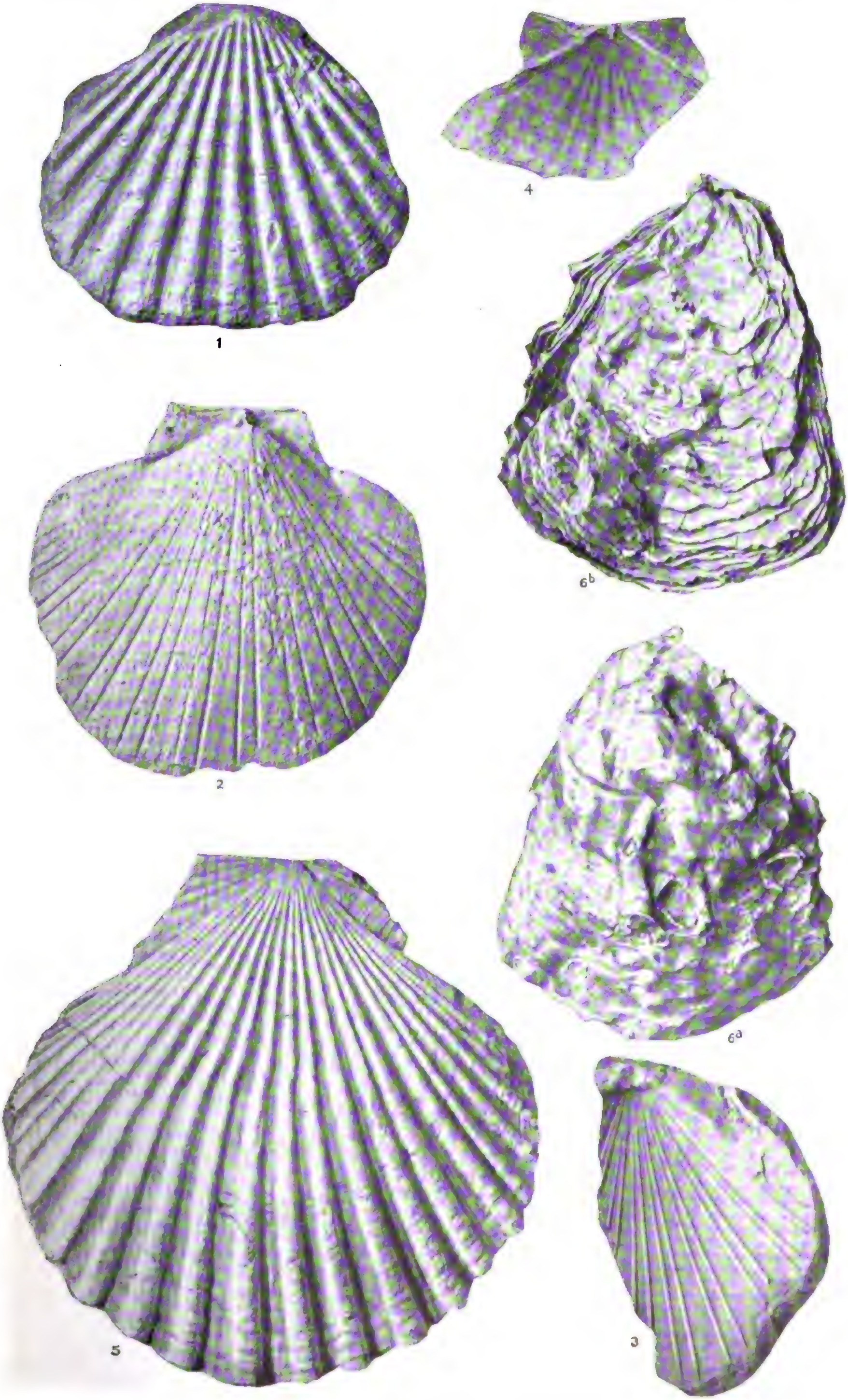
Fig. 3. *Pecten (Amusium) lompocensis* Arnold. U.S.N.M. 164852. Paratype. Interior of a portion of left valve; altitude 90 mm. Ojai Valley, Ventura County, Cal.

Fig. 4. *Pecten (Amusium) lompocensis* Arnold. Collection of California Academy of Sciences. Paratype. Imperfect mold of interior of right valve; hinge line 42 mm. Same locality as fig. 2.

Fig. 5. *Pecten (Lyropecten) bowersi* Arnold. Collection of University of California. Type. Exterior of slightly imperfect right valve; altitude 150 mm. Santa Ynez Canyon.

Fig. 6*a*. *Ostrea eldridgei* Arnold. U.S.N.M. 165320. Left valve; altitude 114 mm. View of exterior. El Jaro Creek (4519). Characteristic of this horizon.

Fig. 6*b*. View of exterior of right valve of same specimen.



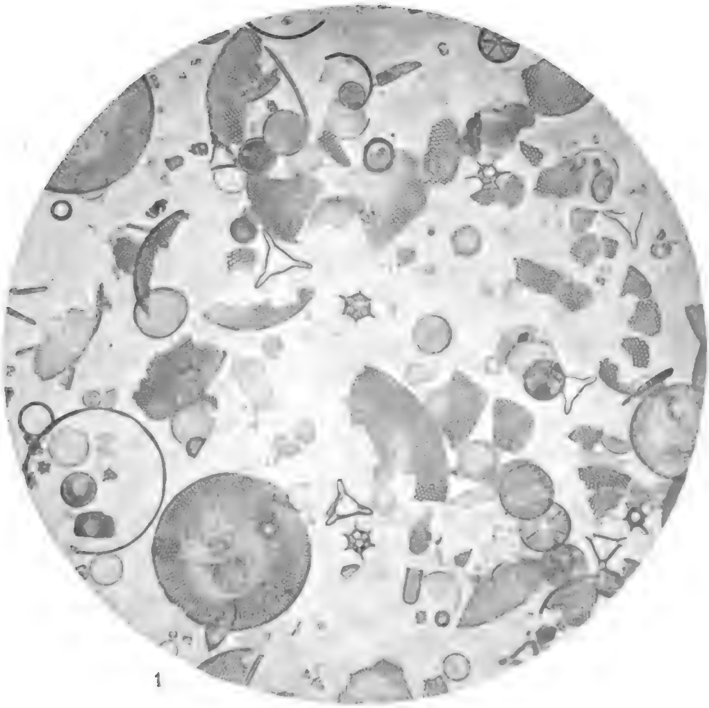
VAQUEROS (LOWER MIOCENE) PELECYPODA

PLATE XIX.

Monterey (Middle Miocene) Diatoms.

Fig. 1. Photomicrograph of slide of partially cleaned diatomaceous shale material from the Lompoc quadrangle, × 100. All the larger individuals and fragments are *Coscinodiscus oculus iridis* Ehrenberg.

Fig. 2. Photomicrograph of slide of diatoms from the Monterey shale at Santa Monica, Los Angeles County, Cal , × 60. Nearly all the species shown on this slide occur in the diatomaceous deposits in the Santa Maria district.



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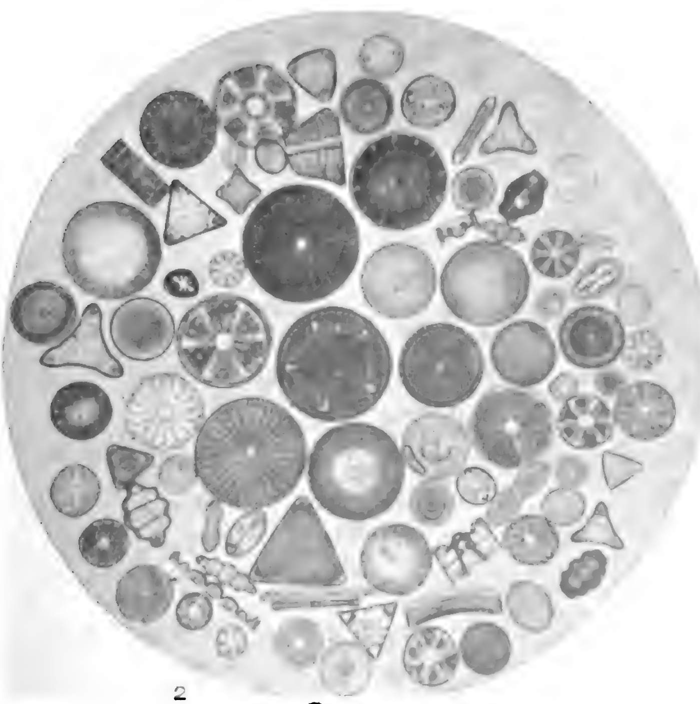

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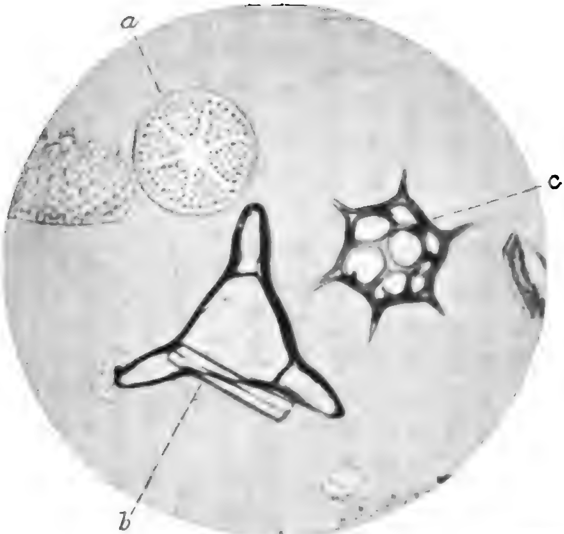
MONTEREY (MIDDLE MIOCENE) DIATOMS.

1784—Bull. 322—07——10

PLATE XX.

Monterey (Middle Miocene) Diatoms.

Fig. 1*a*. *Actinoptychus undulatus* Ehrenberg.
Fig. 1*b*. *Lithodesmium cornigerum* Brun.
Fig. 1*c*. *Dictyocha gracilis* (not a diatom; nature unknown). Enlargement to 1,000 diameters of a portion of the slide shown in Pl. XIX, fig. 1.
Fig. 2. *Coscinodiscus obscurus* A. S., × 1,000. From the Monterey shale of the Santa Maria district.
Fig. 3. *Coscinodiscus subtilis* Ehrenberg, × 1,000. From the Monterey shale of the Santa Maria district.
Fig. 4. *Coscinodiscus robustus* Grev., × 1,000. From the Monterey shale of the Santa Maria district.



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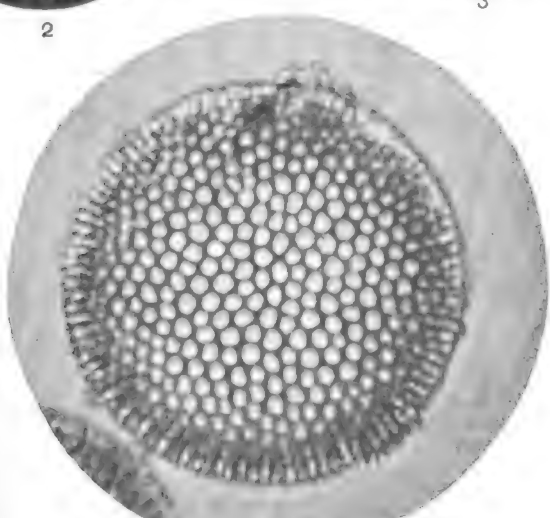

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MONTEREY (MIDDLE MIOCENE) DIATOMS.

PLATE XXI.

FERNANDO (PLIOCENE) GASTEROPODA.

(Unless otherwise indicated figures are natural size.)

FIG. 1. *Trochita radians* Lamarck. U.S.N.M. 165310. Maximum diameter of fragment 20 mm. View of top, × 2. Fugler Point asphalt mine, near Gary (4475). Characteristic of the upper Miocene and lower Pliocene of this region.

FIG. 2. *Priene oregonensis* Redfield (young). U.S.N.M. 165262. Altitude 46 mm. Aperture view. Waldorf asphalt mine (4473). Also known recent.

FIG. 3. *Lunatia lewisii* Gould. U.S.N.M. 165264. Young specimen; altitude 23 mm. Aperture view, × 2. Waldorf asphalt mine (4473). Also known recent.

FIG. 4. *Thalotia caffea* Gabb. U.S.N.M. 165298. Latitude 29 mm. Back view. Fugler Point asphalt mine, near Gary (4475). Also known recent.

FIG. 5. *Thalotia caffea* Gabb. U.S.N.M. 165297. Latitude of fragment 21 mm. View of side of fragment, slightly tilted up. Same locality as fig. 4.

FIG. 6. *Lymnæa alamosensis* Arnold. U.S.N.M. 165426. Type. Altitude 6 mm. Aperture view, × 6. Fresh-water beds, 1 mile southeast of bench mark 425, Los Alamos Valley.

FIG. 7. *Lymnæa alamosensis* Arnold. U.S.N.M. 165426. Young specimen; altitude 3.5 mm. Same locality as fig. 6.

FIG. 8. *Cadulus fusiformis* Sharp and Pilsbry. U.S.N.M. 165267. Longitude 10 mm. Side view, × 3. Waldorf asphalt mine (4473). Known also recent.

FIG. 9. *Cancellaria crawfordiana* Dall var. *fugleri* Arnold. U.S.N.M. 165322. Type. Altitude 22.5 mm. Aperture view, × 2. Fugler Point asphalt mine, near Gary (4475). Characteristic of this horizon.

FIG. 10. *Ocinebra micheli* Ford var. *waldorfensis* Arnold. U.S.N.M. 165261. Type. Altitude 11 mm. Aperture view, × 3. Waldorf asphalt mine (4473).

FIG. 11. *Turritella cooperi* Carpenter. U.S.N.M. 165273. Altitude 34 mm. Aperture view, × 2. Waldorf asphalt mine (4473). Common in the Pliocene and Pleistocene.

FIG. 12. *Drillia waldorfensis* Arnold. U.S.N.M. 165270. Type. Altitude 18.5 mm. Aperture view of imperfect specimen, × 2. Waldorf asphalt mine (4473). Characteristic of this horizon.

FIG. 13. *Drillia johnsoni* Arnold. U. S. N.M. 165263. Altitude 34 mm. Back view, × 2. Waldorf asphalt mine (4473). Also found fossil at San Pedro.

FIG. 14*a*. *Neverita recluziana* Petit. U.S.N.M. 165323. Altitude 35 mm. Aperture view. Fugler Point asphalt mine near Gary (4475). Also known recent.

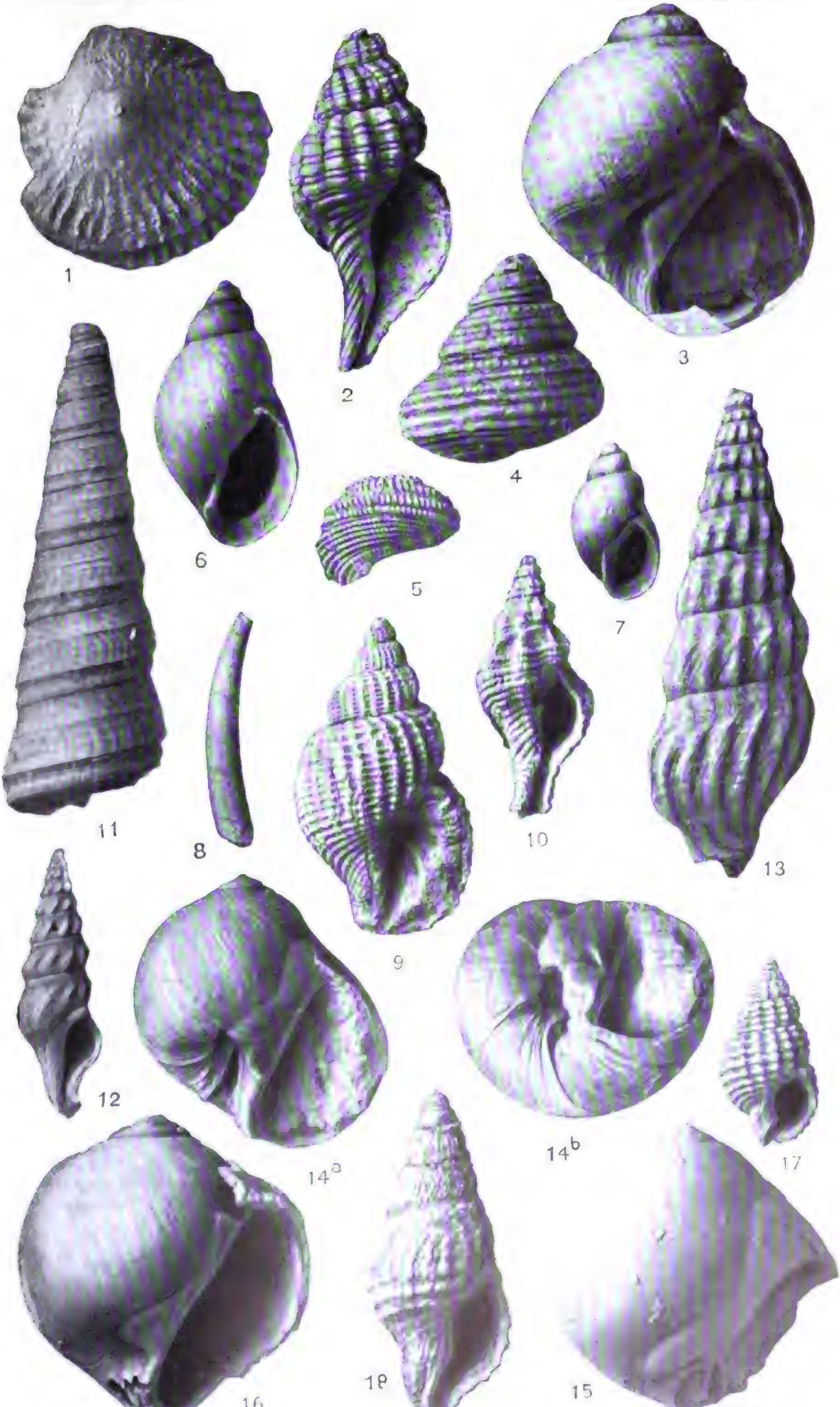
FIG. 14*b*. View of base of same specimen.

FIG. 15. *Neverita recluziana* Petit. U.S.N.M. 165299. Altitude 20 mm. Aperture view, × 2. Fugler Point asphalt mine, near Gary (4475). Also known recent.

FIG. 16. *Natica clausa* Broderip and Sowerby. U.S.N.M. 165269. Altitude 21 mm. Aperture view, × 2. Waldorf asphalt mine (4473). Also known recent.

FIG. 17. *Nassa waldorfensis* Arnold. U.S.N.M. 165272. Type. Altitude 13 mm. Aperture view, × 2. Waldorf asphalt mine (4473). Characteristic of this horizon.

FIG. 18. *Drillia graciosana* Arnold. U.S.N.M. 165309. Type. Altitude 14 mm. Aperture view, × 3. Graciosa Ridge, near Orcutt (4476). Characteristic of this horizon.



FERNANDO (PLIOCENE) GASTEROPODA.

PLATE XXII.

FERNANDO (PLIOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.)

FIG. 1*a*. *Pholadidea ovoidea* Gould. U.S.N.M. 165277. Longitude 58 mm. View of valve. Waldorf asphalt mine (4473). Also known recent.

FIG. 1*b*. View of hinge region of both valves.

FIG. 2. *Purpura crispata* Chemintz. U.S.N.M. 165278. Altitude 20 mm. Aperture view. One mile north of Schumann (4474). Also known recent.

FIG. 3*a*. *Leda taphria* Dall. U.S.N.M. 165296. Longitude 10.5 mm. View of exterior, × 3. Fugler Point asphalt mine, near Gary (4475). Also known recent.

FIG. 3*b*. View of hinge region of both valves.

FIG. 4*a*. *Terebratalia occidentalis* Dall. U.S.N.M. 165300. Ventral valve; latitude 30 mm. View of exterior. Fugler Point asphalt mine, near Gary (4475). A variable species. Also known recent.

FIG. 4*b*. View of dorsal valve of same specimen.

FIG. 5. *Macoma nasuta* Conrad. U.S.N.M. 165276. Longitude 47 mm. View of right valve. Waldorf asphalt mine (4473). Also known recent and in Miocene.

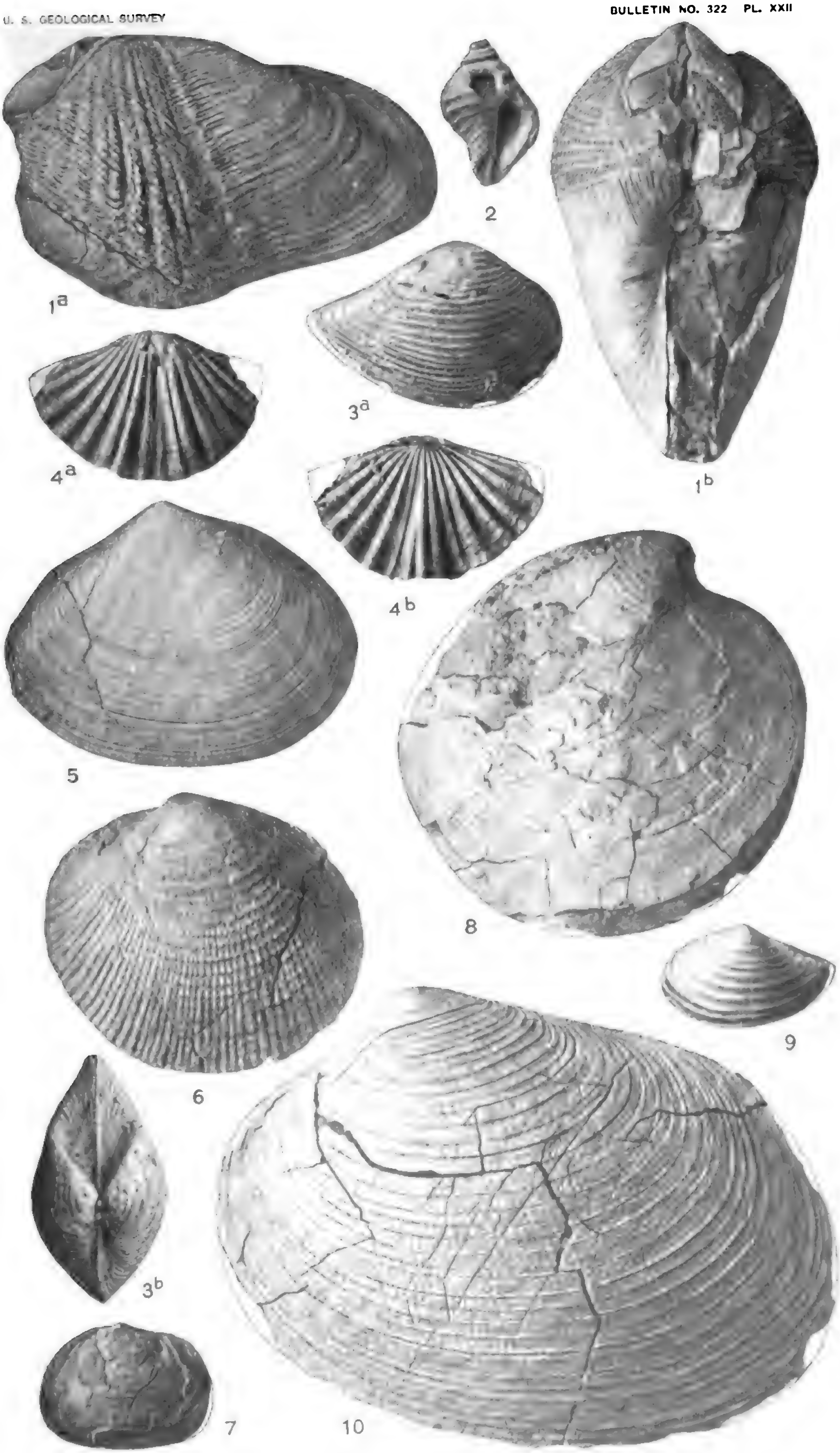
FIG. 6. *Phacoides nuttalli* Conrad var. *antecedens* Arnold. U.S.N.M. 165290. Type. Left valve; longitude 23 mm. View of exterior, × 2. Alcatraz asphalt mine, near Sisquoc (4471). Characteristic of this horizon.

FIG. 7. *Cryptomya ovalis* Conrad. U.S.N.M. 165289. Left valve; longitude 23 mm. Alcatraz asphalt mine, near Sisquoc (4471). Characteristic of this horizon.

FIG. 8. *Dosinia ponderosa* Gray. U.S.N.M. 165295. Right valve; altitude 105 mm. View of exterior, × ½. Alcatraz asphalt mine, near Sisquoc (4471). Also known recent.

FIG. 9. *Leda orcutti* Arnold. U.S.N.M. 165271. Type. Longitude 7 mm. View of exterior, × 3. Waldorf asphalt mine (4473). Characteristic of this horizon.

FIG. 10. *Tapes tenerrima* Carpenter. U.S.N.M. 165293. Left valve; longitude 83 mm. View of exterior. Alcatraz asphalt mine, near Sisquoc (4471). Common in the Pliocene Also known recent.



FERNANDO (PLIOCENE) FOSSILS.

PLATE XXIII.

FERNANDO (PLIOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.)

FIG. 1. *Spisula sisquocensis* Arnold. U.S.N.M. 165292. Type. Left valve; longitude 120 mm. View of exterior, × ½. Alcatraz asphalt mine, near Sisquoc (4471). Characteristic of this horizon.

FIG. 2. *Clidiophora punctata* Carpenter. U.S.N.M. 165302. Right valve; longitude 36 mm. View of exterior. Graciosa Ridge, near Orcutt (4476). Also known recent.

FIG. 3. *Clidiophora punctata* Carpenter. U.S.N.M. 165283. Left valve; longitude 35 mm. View of interior. Graciosa Ridge, near Orcutt (4476). Also known recent.

FIG. 4. *Venericardia californica* Dall. U.S.N.M. 165274. Altitude 29 mm. Aperture view. Waldorf asphalt mine (4473). Characteristic of this horizon.

FIG. 5. *Cumingia californica* Conrad. U.S.N.M. 165311. Left valve; longitude 17 mm. View of exterior, × 2. Fugler Point asphalt mine, near Gary (4475). Also known recent.

FIG. 6. *Spisula catilliformis* Conrad var. *alcatrazensis* Arnold. U.S.N.M. 165291. Type. Right valve; longitude 128 mm. View of exterior, × ½. Alcatraz asphalt mine, near Sisquoc (4471). Characteristic of this horizon.

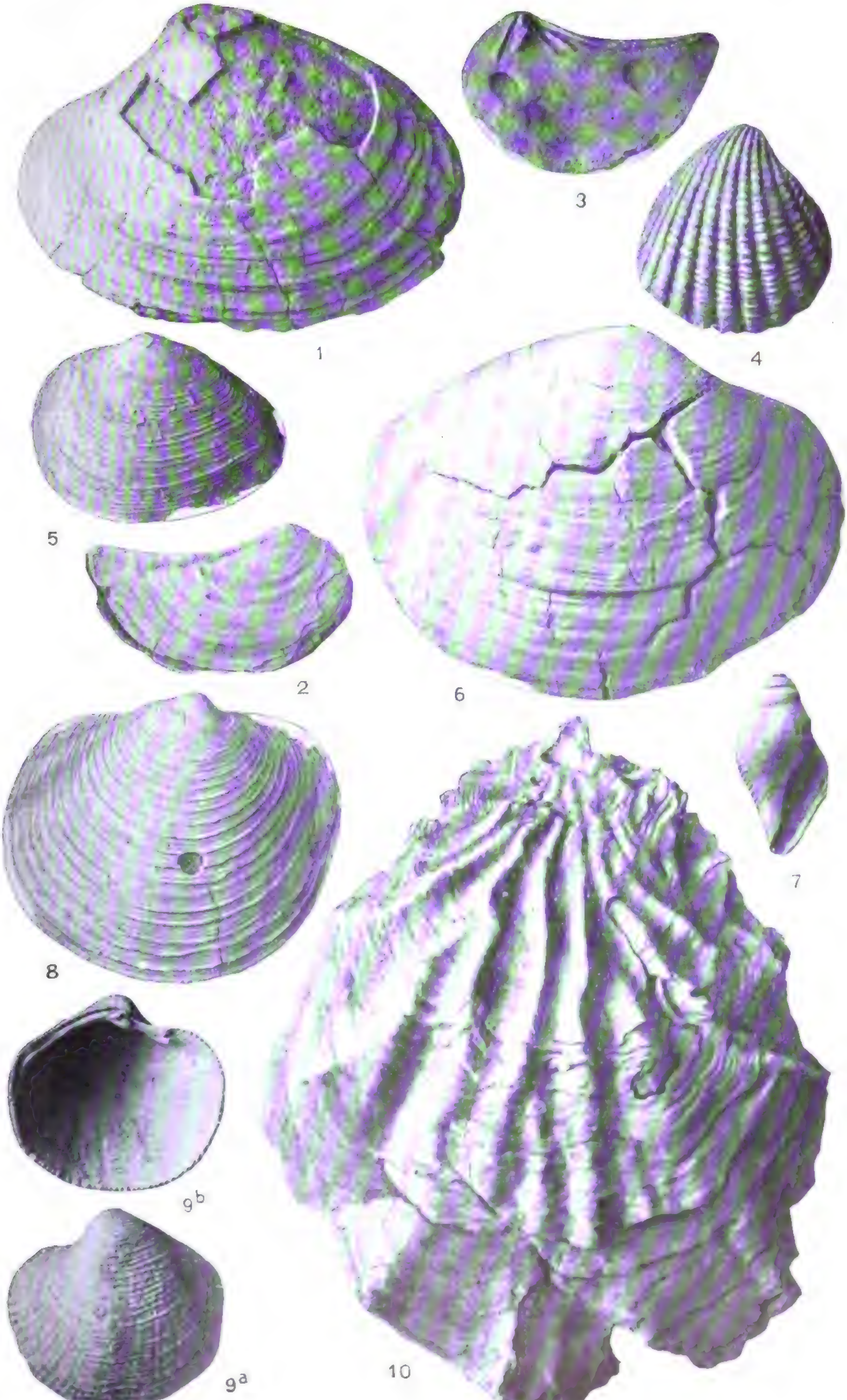
FIG. 7. *Bathytoma carpenteriana* Gabb var. *fernandoana* Arnold. U.S.N.M. 165303. Type. Altitude 24 mm. Aperture view. Graciosa Ridge, near Orcutt (4476). Characteristic of this horizon.

FIG. 8. *Phacoides annulatus* Reeve. U.S.N.M. 165286. Right valve; longitude 45 mm. View of exterior. One mile north of Schumann (4474). Common in the Fernando and also found recent.

FIG. 9*a*. *Phacoides intensus* Dall. U.S.N.M. 165260. Left valve; altitude 6.5 mm. View of exterior, × 4. Waldorf asphalt mine (4473). Found also in same horizon at San Diego.

FIG. 9*b*. View of interior of same specimen, × 4.

FIG. 10. *Ostrea veatchii* Gabb. U.S.N.M. 165282. Left valve; altitude 96 mm. View of exterior. One mile north of Schumann (4474). Characteristic of this horizon.



FERNANDO (PLIOCENE) FOSSILS.

PLATE XXIV.

Fernando (Pliocene) Fossils.

(Unless otherwise indicated all figures are natural size.)

Fig. 1. *Crepidula princeps* Conrad. U.S.N.M. 165268. Longitude 76 mm. Side view. Waldorf asphalt mine (4473). Known only in the fossil state, and found in Santa Barbara County only in the Fernando formation, although it is known from the lower Miocene farther north.

Fig. 2. *Crepidula princeps* Conrad. U.S.N.M. 165315. Longitude 106 mm. View of interior, showing deck. Packards Hill, Santa Barbara.

Fig. 3. *Astyris richthofeni* Gabb. U.S.N.M. 165266. Altitude 14 mm. Aperture view, × 2. Waldorf asphalt mine (4473). So far known only as fossil.

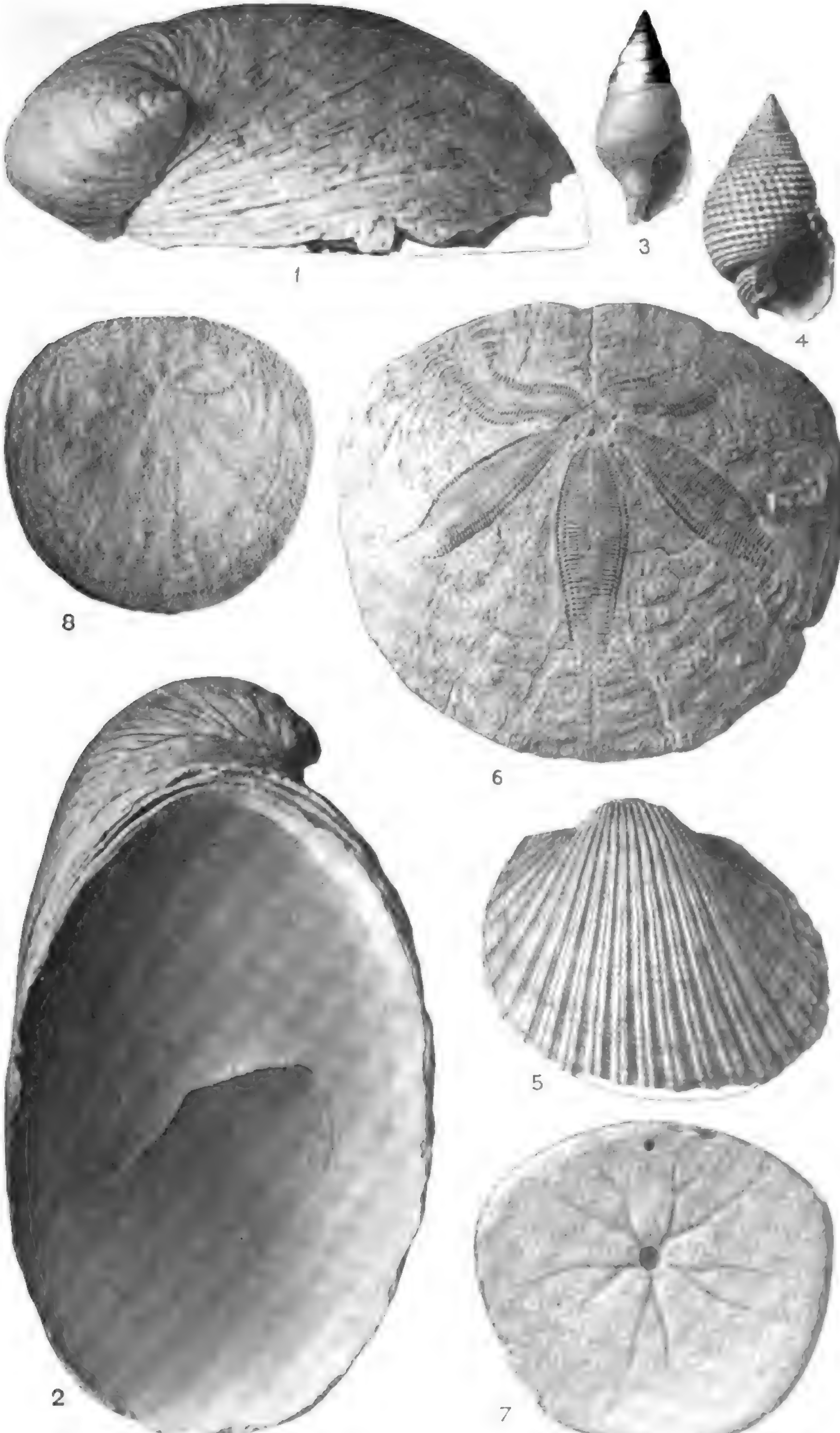
Fig. 4. *Nassa californiana* Conrad. U.S.N.M. 165304. Altitude 30 mm. Aperture view. Graciosa Ridge, near Orcutt (4477). Characteristic of this horizon in the Santa Maria district.

Fig. 5. *Arca trilineata* Conrad. U.S.N.M. 165301. Left valve; longitude 46 mm. View of exterior. Fugler Point asphalt mine, near Gary (4475). Common in the Fernando and equivalent formations and also found in the Monterey.

Fig. 6. *Echinarachnius ashleyi* Merriam. U.S.N.M. 165259. Maximum diameter 69 mm. View from above. Graciosa Ridge, near Orcutt (4469).

Fig. 7. *Echinarachnius ashleyi* Merriam. U.S.N.M. 165259. Maximum diameter 47 mm.. View from below. Same locality as fig. 6.

Fig. 8. *Echinarachnius excentricus* Eschscholtz var. U.S.N.M 165285. Maximum diameter 41 mm. View of top. One mile north of Schumann (4474). This variety is probably characteristic of this horizon.



FERNANDO (PLIOCENE) FOSSILS.

PLATE XXV.

FERNANDO (PLIOCENE) PECTENS.

(Unless otherwise indicated all figures are two-thirds natural size.)

FIG. 1*a*. *Pecten (Pecten) stearnsii* Dall. U.S.N.M. 148008. Right valve; altitude 87 mm. View of exterior. San Diego formation (Pliocene), Pacific Beach, San Diego County, Cal. Common in the Fernando formation of southern California.

FIG. 1*b*. Same specimen as fig. 1*a*. Exterior of left valve.

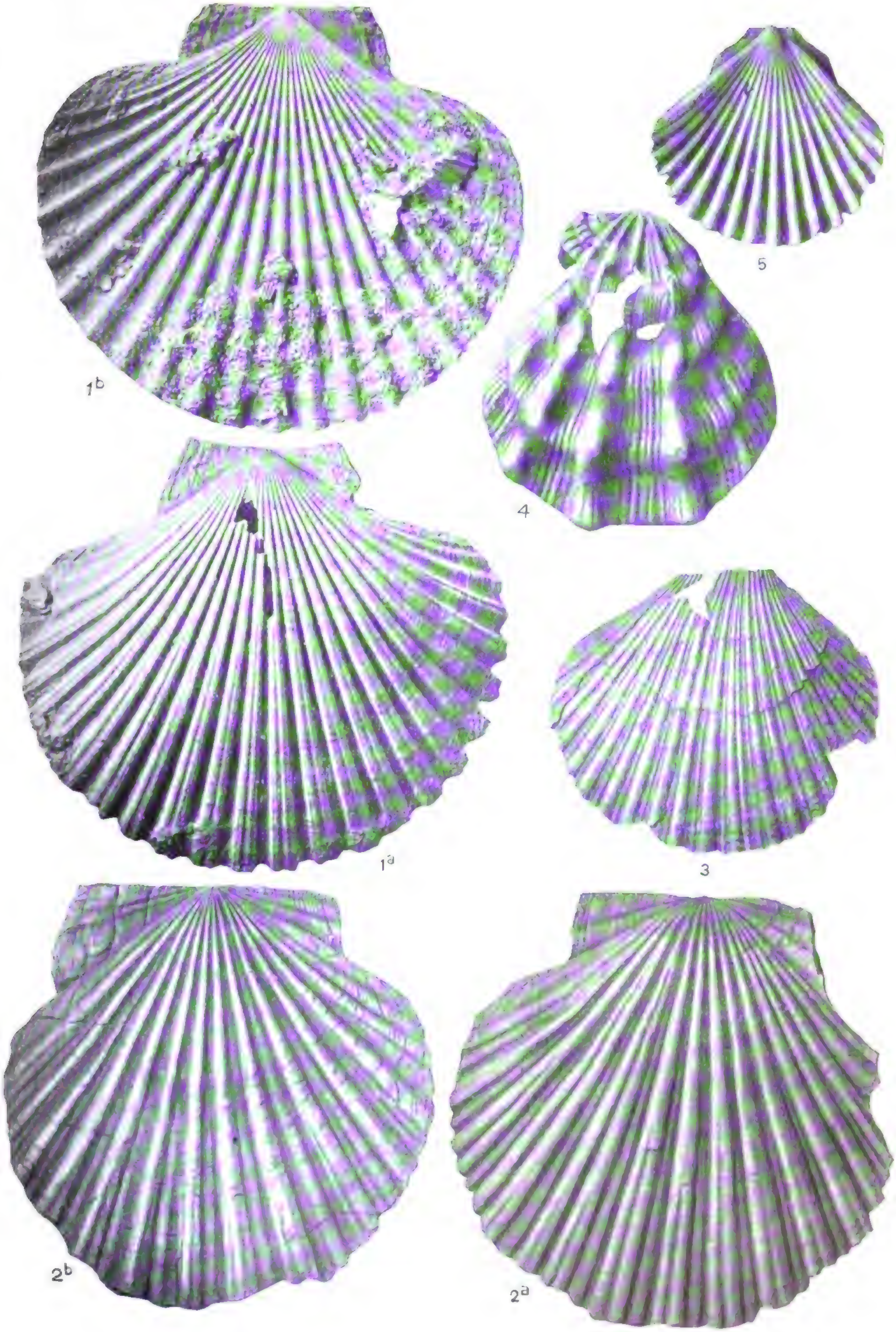
FIG. 2*a*. *Pecten (Patinopecten) oweni* Arnold. Collection of University of California. Type. Right valve, anterior ear slightly broken; altitude 85 mm. View of exterior. Foxen's ranch. Characteristic of this horizon.

FIG. 2*b*. Same specimen as fig. 2*a*. Exterior of left valve.

FIG. 3. *Pecten (Chlamys) lawsoni* Arnold. Collection of California Academy of Science. Type. Right valve (umbo and ears missing); longitude 65 mm. View of exterior. One mile north of Schumann. Characteristic of this horizon.

FIG. 4. *Pecten (Chlamys) wattsi* Arnold. Collection of California Academy of Science. Type. Slightly imperfect left valve; altitude 66 mm. View of exterior. Lower Pliocene, Kreyenhagen's ranch, Fresno County. Common in the Fernando ot southern California.

FIG. 5. *Pecten hemphilli* Dall. U.S.N.M. 165280. Left valve; altitude 22.50 mm. View of exterior, × 1⅔. One mile north of Schumann (4474). Characacteristic of this horizon.



FERNANDO (PLIOCENE) PECTENS

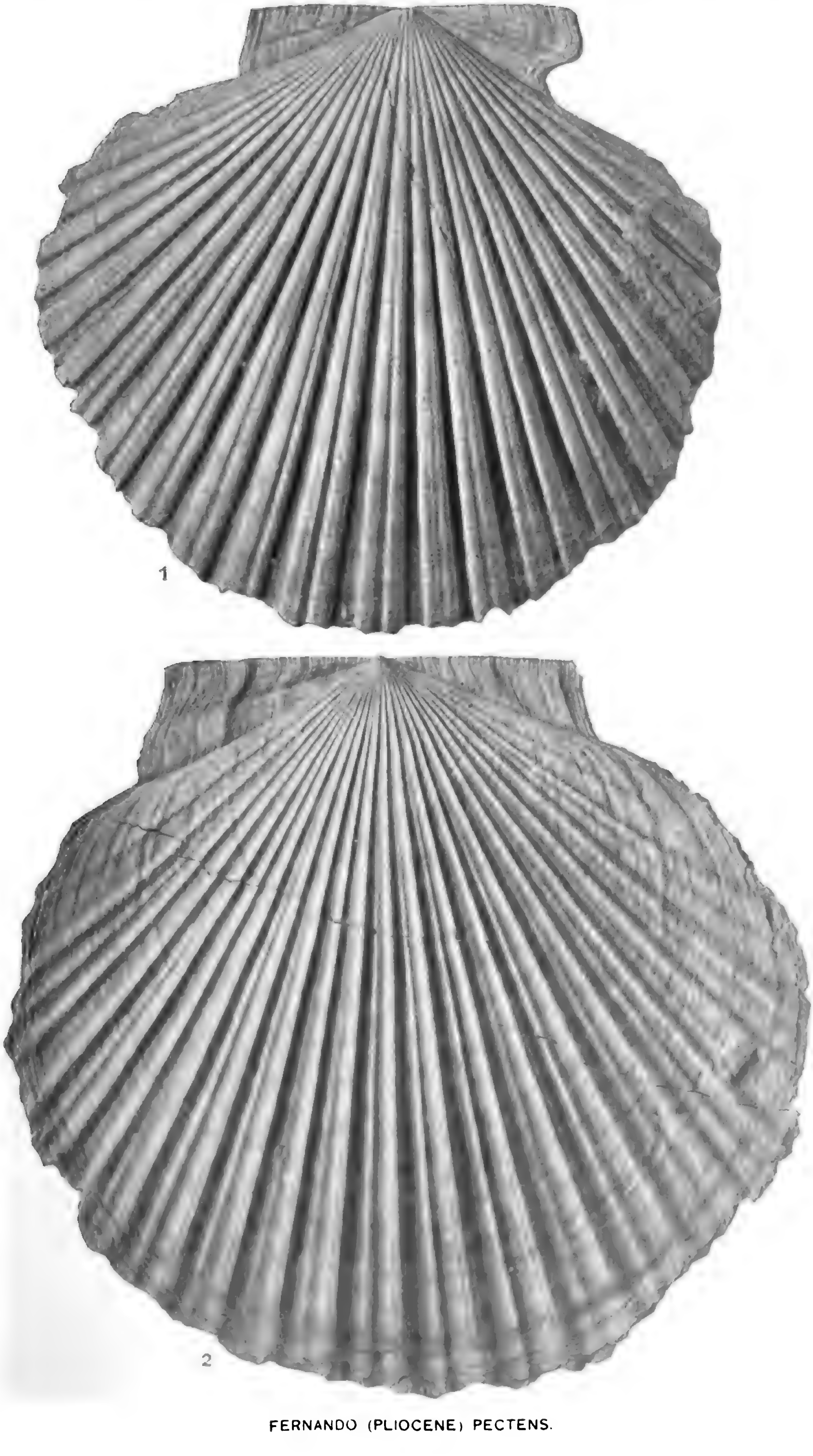
PLATE XXVI.

FERNANDO (PLIOCENE) PECTEN.

(Unless otherwise indicated all figures are two-thirds natural size.)

FIG. 1. *Pecten* (*Patinopecten*) *healeyi* Arnold. U.S.N.M. 148012. Holotype. Right valve; altitude 121 mm. View of exterior. San Diego formation (Pliocene), San Diego County, Cal. Characteristic of the Fernando formation throughout the Coast Range.

FIG. 2. *Pecten* (*Patinopecten*) *healeyi* Arnold. U.S.N.M. 154162. Paratype. Left valve; altitude 141 mm. View of exterior. San Diego formation (Pliocene), Pacific Beach, San Diego County, Cal.



FERNANDO (PLIOCENE) PECTENS.

INDEX.

CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 322.]

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Most of the above publications can be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they can be obtained, free of charge (except classes 2, 7, and 8), on application.
2. A certain number are delivered to Senators and Representatives in Congress for distribution.
3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they can be had at prices slightly above cost.
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The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports; Q, Fuels; R, Structural materials. This paper is the one hundred and third in series A and the one hundred and twenty-seventh in series B, the complete lists of which follow (PP=Professional Paper; B=Bulletin; WS=Water-Supply Paper):

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EXPERIMENTAL WORK

CONDUCTED IN THE

CHEMICAL LABORATORY

OF THE

UNITED STATES FUEL-TESTING PLANT AT ST. LOUIS, MO.

JANUARY 1, 1905, TO JULY 31, 1906

BY

N. W. LORD

WASHINGTON

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CONTENTS.

EXPERIMENTAL WORK CONDUCTED IN THE CHEMICAL LABORATORY OF THE UNITED STATES FUEL-TESTING PLANT, ST. LOUIS, JANUARY 1, 1905, TO JULY 31, 1906.

By N. W. Lord.

INTRODUCTION.

The experimental work reported upon herein was performed at the laboratory of the United States fuel-testing plant on the grounds of the Louisiana Purchase Exposition at St. Louis, Mo., between January 1, 1905, and July 31, 1906, and was undertaken for the purpose of checking the results obtained in the routine work of the laboratory, improving the methods of working, and investigating the chemical and physical properties of coal. The laboratory having been designed primarily for the analysis of the coal samples sent to the fuel-testing plant, as well as those taken in connection with the regular testing operations of the boiler, gas-producer, and other divisions of the plant, only a very small proportion of the time of the force was available for experimental work outside of the regular routine.

From the nature of such work it was not possible to separate the results obtained in 1905 from those obtained in 1906, especially as many of the experiments, such as those on the alteration of coal, involved a long time and were started in 1905 and continued to the middle of 1906. This report therefore covers all such work up to its completion in July, 1906.

The complete history of the coals used in these experiments is not given, the samples being usually referred to by their laboratory numbers only, as such information is generally not necessary and does not affect the interpretation of the results obtained in the experiments. Fuller information as to any particular sample may be found in the published reports of the fuel-testing plant for 1905 and 1906.

In the following pages the results of each line of experimental work are given under a special heading indicating the object of the investigation.

While many of the investigations can only be regarded as preliminary, it is believed that the mass of the results will be of value in shedding light on some matters of general interest.

ACCURACY OF METHOD OF TAKING CAR SAMPLES.

The regular method of taking car samples has been fully described under "Sampling" in Professional Paper No. 48, page 175. To check the accuracy of this method, check samples on two cars of coal rather high in moisture, ash, and sulphur were taken at the same time that the regular sample was taken, by opening a gate in the conveyor runway every four or five minutes, and thereby allowing the contents of one or two buckets passing at that time to be emptied into a small bin. In this way a sample of 1,200 to 1,500 pounds was taken during the unloading of the car. This sample was then put through a small crusher, crushed to ½-inch size, and resampled at the conveyor buckets, and a sample was sent to the chemical laboratory for analysis. In the following table the Indiana coal was a run-of-mine coal, and the amount sampled was approximately 20 tons; and the Ohio coal was a run-of-mine coal, and the amount sampled was approximately 26 tons.

Moisture, ash, and sulphur determinations from samples of two cars of run-of-mine coal.

Constituent.	Indiana coal.		Ohio coal.	
	Regular sample.	Check sample.	Regular sample.	Check sample.
Moisture	10.80	10.47	9.01	9.43
Ash	12.62	12.92	11.33	11.59
Sulphur	4.39	4.43	4.02	4.02

For coals containing such high percentages of ash and sulphur the agreement between these independently taken samples is satisfactory. It indicates, so far as the sampling is concerned, that the analytical work may be taken as closely representing the average of the carload.

MOISTURE LOSS IN COARSE SAMPLES FROM STANDING IN COVERED METAL PAILS.

The large samples from the fuel-testing plant were sent to the laboratory in closed metal pails, and some of them were allowed to stand in the pail several hours, or occasionally over night, before sampling. To see if any considerable amount of moisture might be lost in this way, a portion of the wet sample from the washery (Pennsylvania No. 9 coal) was taken as the most favorable case, and allowed to stand for five days in the closed pail in the laboratory before sampling. The average temperature for the five days was 18° C., and the atmospheric humidity 60 per cent. The percentages of moisture determined by

analysis of this sample, and analysis of the portion of the sample reduced at once, are as follows:

	Per cent.
Portion sampled at once	5.07
Portion sampled after standing five days	4.58
Loss by standing	.49

These coals dry down to about 1 per cent moisture, so that the loosely held and surface moisture amounted to about 4 per cent. From this experiment the moisture loss which occurs during the short time that the sample usually is allowed to stand in the laboratory before sampling would appear to be unimportant.

INVESTIGATION OF MOISTURE LOSSES DURING SAMPLING.

In preparing the samples for these tests the coarse sample (40 to 50 pounds in weight), when received at the laboratory, was divided by quartering. One portion of 500 grams was at once ground without air drying in the ball mill. Another portion of about 5 to 10 pounds was air dried in the usual way before the final pulverization. The results (reduced to sample as received) in moisture and ash for the two portions are as follows:

Moisture and ash determinations on air-dried samples and fresh samples of coal.

Designation of sample.	Regular sample (air dried).		Fresh sample (not air dried).	
	Moisture.	Ash.	Moisture.	Ash.
Illinois	13.54	10.74	[a] 9.36	11.87
	13.72	10.32	11.92	10.40
Texas No. 4	33.85	7.30	33.00	7.65
Arkansas No. 8	5.19	14.01	3.58	14.16
Indiana No. 12	10.57	11.65	9.95	11.98
Illinois No. 23 B	15.68	15.59	14.78	16.11
Illinois No. 23 A	13.47	11.53	12.43	11.63
Missouri No. 6	13.80	11.74	12.58	11.15
Illinois No. 22 A	11.91	13.01	11.58	12.57

[a] This sample was ground very fine in ball mill, which probably accounts for the loss being so large.

The results obtained for moisture from the original samples that were ground down without preliminary air drying are without exception decidedly lower than the results obtained from the regularly prepared air-dried samples when calculated to the sample as received, the greatest difference being over 4 per cent and the average difference over 1½ per cent. Furthermore, the fine sample, after being ground without previous air drying, as shown by experiments (see pp. 13-17), gives up moisture so readily as to indicate that a large additional loss during the handling and weighing of the sample in the laboratory is almost certain. The consequent errors due to moisture losses are liable to be so large as to affect very seriously the accuracy of the results obtained.

DETERMINATION OF ERRORS DUE TO ABRASION OF PEBBLES USED IN BALL MILL.

During the Louisiana Purchase Exposition the final pulverization of the samples was done on a bucking board. In the work done during 1905 the final grinding of the sample was done in closed jars in the ball mill, quartz pebbles being used.

In order to determine whether there was danger of materially increasing the ash contents of the samples from chipping and abrasion of the pebbles used in grinding, these pebbles were carefully weighed at intervals and the amount of loss determined. The weight of the sample ground each time in the ball mill is approximately 500 grams, and the abrasion of the pebbles (calculated as percentage of the weight of the samples ground) was also carefully determined. The results on three weighed lots of pebbles are as follows:

Losses of weight in three lots of quartz pebbles before and after grinding in the ball mill.

Lot.	Total weight of samples ground.	Weight of pebbles.		Loss by abrasion.	
		Before grinding	After grinding.	Actual.	Ratio to coal ground.
	Grams.	*Grams.*	*Grams.*	*Grams.*	*Per cent.*
No. 1 (250 samples ground)	125,000	4,118.6	4,113.1	5.5	0.004
No. 2 (230 samples ground)	115,000	3,502.9	3,499.4	3.5	.003
No. 3 (245 samples ground)	122,500	4,273.2	4,268.3	4.9	.004

These results show that as far as the fine pulverization of the coal is concerned, there is little or no danger of increasing the ash content of the sample appreciably by using quartz pebbles as the grinding medium. The pebbles used show no tendency to chip, as the loss between weighings taken before and after 25 to 50 samples were ground in no case amounted to over 1 gram, the abrasion being in all cases approximately proportional to the weight of samples ground.

COMPARISON OF RESULTS OF AIR DRYING IN THE SPECIAL OVEN AND BY EXPOSURE.

The samples as received at the laboratory were dried to approximately an air-dry condition, before their final pulverization, in an oven especially designed for this purpose. To find out how nearly this method of drying approximates air drying under ordinary conditions, the following tests were made:

The loss in weight of samples of different coals allowed to air dry under observed conditions of temperature and humidity was determined by allowing portions of the coarse samples spread on trays to remain exposed to the air of the laboratory for periods of time ranging from seven to twenty days. The samples were weighed from time

to time and the drying continued until the weight remained almost constant. The air-drying loss of these samples and the loss in weight of the corresponding regular samples dried in the dryer, with the amount of moisture remaining in the dryer samples, are tabulated below. In most of the samples the dryer loss is not widely different from the loss on the air-dry sample. Special exceptions are Nos. 1960 (Indiana No. 9 B) and 1390 (Wyoming No. 6), on which samples the dryer-sample loss is decidedly larger than that on the samples dried by exposure to the air of the laboratory. The samples dried during the summer months were exposed to air of a high average humidity (60 per cent), as the temperature and humidity of the laboratory were approximately that of the outdoor air for that period. The samples dried during the winter months were exposed to air of low average humidity (30 per cent), as the temperature of the laboratory was decidedly higher than that of the outdoor air, with approximately the same absolute amount of moisture present in the laboratory and in the outdoor air. The humidity of the warmer laboratory air is consequently low. The percentage of moisture remaining in the samples dried by exposure to the air of the laboratory was determined by adding or subtracting (according to whether it was plus or minus) the difference between the loss in the dryer and the loss in the exposed sample to the moisture remaining in the "dryer sample," as given in the table below:

Results of tests for moisture in samples of coal.

Sample of coal.		Moisture in sample.						Air of laboratory.	
			Loss on coarse sample, as dried—		After drying—				
Laboratory number.	Field number.	As received	By exposure.	In dryer.	By exposure (calculated).	In dryer.	Time of drying by exposure	Temperature	Humidity.
		Per ct	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Days.*	*° C.*	*Per ct.*
3294	New Mexico No. 5	2.72	1.60	1.40	1.14	1.34	17	25	63
3255	Alabama No. 3	2.72	0.30	1.20	2.44	1.54	13	25	64
3308	New Mexico No. 3	2.75	1.40	1.40	1.37	1.37	19	25	63
3331	New Mexico No. 4 A	2.78	0.40	1.40	2.40	1.40	11	24	62
3406	Indian Territory No. 2 B	2.81	0.60	1.40	2.23	1.43	16	26	64
2626	West Virginia No. 20	2.89	1.98	1.90	0.93	1.01	16	21	26
3315	New Mexico No. 4 B	3.38	1.60	1.70	1.81	1.71	18	25	62
3295	New Mexico No. 3 A	3.45	1.50	2.00	1.98	1.48	17	25	63
2332	West Virginia No. 17	3.46	2.07	2.50	1.43	1.00	11	21	47
2572	West Virginia No. 21	3.57	2.24	2.10	1.36	1.50	12	19	28
2420	Virginia No. 1	4.06	2.59	2.40	1.51	1.70	9	25	27
3307	New Mexico No. 3 B	4.36	2.20	3.00	2.20	1.40	19	25	63
2528	Kentucky No. 5	4.36	1.77	2.80	2.63	1.60	10	24	31
2264	West Virginia No. 16 B	5.57	3.89	4.40	1.73	1.22	11	18	57
3286	Utah No. 1	5.83	2.30	2.10	3.61	3.81	17	25	63
3405	Indian Territory No. 2 B	6.27	4.20	4.90	2.14	1.44	16	26	64
1761	Illinois No. 15	9.95	3.62	4.20	6.58	6.00	18	27	64
1876	Indiana No. 6	10.47	6.02	6.30	4.73	4.45	14	27	64
3225	Wyoming No. 5	11.44	4.10	3.70	7.64	8.04	21	25	53
2896	Illinois No. 22 B	13.03	9.74	11.20	3.52	2.06	8	23	35
1960	Indiana No. 9 B	13.53	7.13	10.70	6.74	3.17	18	27	67
2686	Washington No. 1 B	14.30	8.12	9.60	6.68	5.20	9	22	28
2731	Illinois No. 20	14.68	11.80	12.40	3.20	2.60	11	23	34
2803	Illinois No. 23 B	15.68	13.98	13.20	2.08	2.86	10	24	31
3390	Wyoming No. 6	19.00	7.50	11.30	12.48	8.68	16	27	64

These values show that on most of the coals tested drying in the drier brought the sample to approximately an air-dry condition. No effort had been made to do more than this, as the primary object in the air drying is to get the sample into such a condition that the fine sample will not be subject to large moisture changes during subsequent handling in the laboratory. The air drying, therefore, is not to be understood as being a rigidly fixed determination; but it has been found that the values obtained as a rule are within a sufficiently definite range to give this determination some importance as showing the effect of standing and exposure on the percentage of moisture in the coal. This matter is of considerable commercial importance, since, so far as the moisture content is concerned, coals having a large air-drying loss are obviously much more affected than coals having a small air-drying loss. It further has appeared that the amount of residual moisture in the air-dried sample prepared under the described conditions usually lies within a range which is somewhat characteristic of different kinds of coal.

The foregoing table shows this residual moisture to be about 1 per cent in the West Virginia coals, 3 to 6 per cent in the Illinois and Indiana coals, and from 10 to 12 per cent in the Wyoming samples.

COMPARISON OF RESULTS FOR MOISTURE OBTAINED FROM SAMPLES PULVERIZED BY VARIOUS METHODS.

The possibility of moisture loss during grinding on a bucking board has already been referred to. In order to obtain more data upon different coals and under observed conditions of temperature and humidity, duplicate portions of a number of samples were ground down upon the bucking board and the moisture determinations made upon these portions. At the same time portions of the coal which had only passed the 1 10-inch mesh sieve in the process of sampling were reserved as samples for determining moisture in the coal at this size. The moisture was determined in these samples by drying 5 grams for one hour in the air bath, instead of 1 gram as in the regular determination. The moisture results on these samples and the results upon the regular samples ground down in the ball mill, together with the temperature and humidity conditions of the laboratory at the time of sampling, are given in the following table:

Results for moisture from coal samples variously pulverized.

Sample of coal.		Moisture in sample from—			Air of laboratory.	
Laboratory number.	Field number.	Bucking board.	Ball mill.	1/10-inch mesh sieve.	Temperature.	Humidity.
		Per cent.	*Per cent.*	*Per cent.*	° C.	*Per cent.*
3255	Alabama No. 3	1.43	1.54	1.43	29	66
2689	Arkansas No. 1 B	0.89	0.85	0.69	23	30
2688	Arkansas No. 7 A, 7 B	0.62	0.60	0.50	23	30
2722	Arkansas No. 7 B	0.94	1.05	0.87	23	30
2744	Arkansas No. 8	0.75	0.83	0.81	28	37
2690	Arkansas No. 9	1.22	1.11	1.03	23	30
1835	Brazil	5.40	4.95	4.80	30	67
1680	California No. 1		9.05	[a] 7.28	29	60
1699	.....do		8.89	7.42	22	61
1702	Illinois No. 6 B		4.17	4.22	27	52
1780	Illinois No. 7 D	6.82	7.60	7.48	24	70
1635	Illinois No. 9 A	4.92	4.99	5.36	20	59
1639	Illinois No. 9 B		4.03	3.73	25	39
1638	.....do	10.58	12.34	12.35	21	60
1648	Illinois No. 10		2.79	2.94	28	37
1653	Illinois No. 11 A		2.98	2.59	24	55
1654	.....do		3.11	2.82	24	55
1717	Illinois No. 11 C	2.97	2.42	2.39	27	64
1802	Illinois No. 11 D	6.06	6.30	6.01	26	64
1786	Illinois No. 13	4.22	3.89	3.68	25	63
1740	Illinois No. 14	5.24	5.19	5.29	35	53
1761	Illinois No. 15	6.10	6.00	5.84	25	77
1820	Illinois No. 16	4.74	4.61	4.46	28	72
1926	Illinois No. 19 A	6.46	6.39	6.20	31	56
3417	Illinois No. 19 C	5.43	6.01	5.57	33	19
3448	Illinois No. 19 D	3.98	3.87	3.95	33	49
3451	.....do	4.83	5.27	4.96	33	49
2731	Illinois No. 20	2.89	2.60	2.57	25	39
2852	Illinois No. 21	4.42	5.74	5.61	23	30
2905	Illinois No. 22 A	4.45	6.39	6.39	24	20
2896	Illinois No. 22 B	2.14	2.06	1.86	24	20
2803	Illinois No. 23	2.47	2.86	2.65	24	31
2819	Illinois No. 23 A	2.05	2.23	1.93	22	28
1941	Indiana No. 3	5.19	5.12	4.93	29	60
1844	Indiana No. 4	4.01	3.58	3.42	28	72
1859	Indiana No. 5	5.62	5.21	5.60	21	68
1875	Indiana No. 6	5.76	5.91	5.71	21	60
1881	Indiana No. 7 A	5.60	5.50	5.46	27	71
2037	Indiana No. 8	3.99	5.19	5.16	23	69
1960	Indiana No. 9 B	3.30	3.17	3.04	28	72
1979	Indiana No. 10	2.98	2.85	2.62	31	63
2087	Indiana No. 11	7.92	8.49	8.52	22	75
2759	Indiana No. 12	3.45	4.45	4.29	19	35
3405	Indian Territory No. 2 B	1.70	1.44	1.34	31	63
3406	.....do	1.65	1.43	1.38	31	63
2843	Kansas No. 6	1.71	2.09	1.83	24	25
2528	Kentucky No. 5	1.66	1.60	1.34	23	37
2592	Kentucky No. 6	2.66	2.99	2.80	22	28
2274	Maryland No. 1	1.12	0.94	0.99	24	70
2865	Missouri No. 5	1.59	1.71	1.55	24	25
2904	Missouri No. 6	1.63	2.49	2.62	24	31
2937	Missouri No. 7	5.25	7.41	7.45	21	33
2942	.....do	2.54	2.48	2.28	20	37
3295	New Mexico No. 3	1.03	1.48	1.34	30	57
3307	New Mexico No. 3 B	1.43	1.40	1.38	28	65
3308	.....do	1.33	1.37	1.33	25	65
3315	New Mexico No. 4	1.56	1.71	1.64	28	43
3331	New Mexico No. 4 A	1.54	1.40	1.14	31	47
3294	New Mexico No. 5	1.36	1.34	1.24	30	67
2071	Ohio No. 1	3.40	2.96	2.65	21	75
2109	Ohio No. 2	5.60	5.60	5.57	27	72
2144	Ohio No. 3	5.43	6.24	6.15	18	73
2083	Ohio No. 4	2.56	2.16	1.94	24	85
2062	Ohio No. 5	2.25	1.99	1.84	18	73
2310	Ohio No. 9 A	2.55	2.47	2.56	19	66
2311	Ohio No. 9 B	2.78	2.65	2.37	19	66
2115	Pennsylvania No. 5 A	1.82	1.77	1.77	24	76
2068	Pennsylvania No. 5 B	1.57	1.47	1.38	21	75
2152	Pennsylvania No. 8	0.77	0.64	0.87	31	53
3102	Tennessee No. 6	1.27	1.02	1.02	24	31
3127	Tennessee No. 8 A	1.01	1.05	0.98	29	38
3128	Tennessee No. 8 B	0.92	1.14	1.02	25	33
2734	Texas No. 3	9.06	9.88	8.48	23	24
2717	Texas No. 4	8.63	9.76	8.67	21	26
3199	Utah No. 1	2.23	2.34	2.32	24	31
2420	Virginia No. 1 A	1.60	1.70	1.60	24	25

[a] Heated two hours, moisture 7.86; heated three hours, moisture 8.03.

Results for moisture from coal samples variously pulverized—Continued.

Sample of coal.		Moisture in sample from—			Air of laboratory.	
Laboratory number.	Field number.	Bucking board.	Ball mill.	$\frac{1}{60}$-inch mesh sieve.	Temperature.	Humidity.
		Per cent.	*Per cent.*	*Per cent.*	° C.	*Per cent.*
2358	Virginia No. 4	2.35	2.40	2.28	28	26
2687	Washington No. 1 A	5.38	5.98	5.85	20	24
2686	Washington No. 1 B	4.55	5.20	4.65	20	24
2250	West Virginia No. 4 B	1.45	1.35	1.19	23	69
2028	West Virginia No. 13	1.10	1.17	1.15	23	69
2004	West Virginia No. 14	2.00	2.05	2.05	34	50
2332	West Virginia No. 17	1.15	1.00	1.00	20	59
2527	West Virginia No. 18	1.29	1.28	1.13	23	37
2549	West Virginia No. 19	0.65	0.68	0.65	22	22
2572	West Virginia No. 21	1.43	1.50	1.44	20	24
2131	Wyoming No. 2 B	4.57	4.65	4.48	23	85
3213	Wyoming No. 5	5.61	6.00	6.04	31	46
3390	Wyoming No. 6	8.90	8.68	8.24	32	55

The results for moisture obtained on the 5-gram portion of the coarse sample, as a rule, run from 0.1 to 0.2 per cent lower than the moisture value as determined upon the sample ground in the ball mill. In a few cases the moisture result on the coarse sample is somewhat higher than the result on the ball-mill sample, while in a few other cases, noticeably the lignite samples from California and Texas, the moisture result on the coarse sample is decidedly lower. This result, as shown by tests on sample 1680, California No. 1, may be ascribed to the fact that the moisture in a coarse sample of lignite is very incompletely expelled by one hour's heating. An additional two hours of heating upon this sample resulted in an increased moisture value of over 0.7 per cent. As a method applied to any and all coals, the determination of the moisture in the fine sample appears to be preferable to the determination in the coarse sample. The results obtained for moisture upon the samples ground down on the bucking board, as compared with the results obtained on the samples ground down in the ball mill, show that the bucking-board samples may either gain or lose moisture, depending on the thoroughness of the preliminary drying of the coarse samples and the humidity of the air in the laboratory at the time of sampling. For Illinois coals previously dried down to a moisture content of about 5 or 6 per cent, the bucking-board sample took up moisture during grinding when the humidity was high (70 per cent or more). On the other hand, with low humidity (20 to 30 per cent), the moisture loss during grinding was considerable, and a careful study of the results obtained upon the bucking-board sample, as compared with the results on the ball-mill sample, taken in connection with the humidity changes, shows that any success in attempting to work the sample down on the bucking board without danger of moisture changes is practically impossible of realization, and that the sample ground down on the bucking board can not be in any case regarded as entirely satisfactory on account of the danger of moisture changes during the sampling. The experiments reported under the

following heading, showing the rapid changes in moisture in coal samples when spread on the watch glass, indicate that there is probably a slight gain or loss of moisture in the ball-mill sample even during the short time that this sample is exposed to air during sampling, and that this change may be considerable if the coarse sample be very far from an air-dried condition before being ground down. The grinding down of samples in the ball mill can not, therefore, be considered as perfectly satisfactory in so far as moisture changes are concerned; but this method of grinding, in connection with the preliminary drying of the coarse sample, is much more satisfactory and reliable than any other practical method that has been devised of which the writer has any knowledge. Therefore it appears that the handling of samples in this manner, as compared with the practice in most general use, is an important step in the direction of securing a sample for analysis with a minimum amount of unaccounted-for changes in moisture.

CHANGES IN MOISTURE CONTENT OF FINE SAMPLES OF COAL UNDER MODIFIED CONDITIONS.

That coal in a fine condition changes rapidly in moisture content is well known. In order to obtain definite information as to the rate of this change a number of tests were made on coals under different conditions. The first selection for testing was a fine sample (No. 1638 C) of undried Illinois coal, containing 12.4 per cent moisture. One gram of this sample was spread out on a 4-inch watch glass and weighed at intervals, a record of the temperature and humidity being taken at the time of the different weighings. A second series of tests was also made on a 10-gram portion of this sample spread upon a 4-inch watch glass. A third series of tests was made upon another portion of this sample (17.2 grams) by allowing it to stand in an open, wide-mouthed 2-ounce bottle and weighing at intervals. The results for these three series of tests are as follows:

Changes in moisture content of sample (No. 1638 C) of undried Illinois coal.

FIRST SERIES—1 GRAM ON 4-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° C.	*Per cent.*
5 minutes	−0.0202	−2.02	22	21
5 minutes	−.0075	−.75		
15 minutes	−.0090	−.90		
1¼ hours	−.0110	−1.10	25	50
24 hours	−.0350	−3.50	24	36
24 hours	−.0120	−1.20	28	36
25 hours	+.0140	+1.40	25	63
42 hours	+.0060	+.60	18	64
104 hours	−.0127	−1.27	27	35
15 days	+.0007	+.07	32	41
48 days	−.0175	−1.75	32	55
Total loss in 72 days		10.42		

Changes in moisture content of sample (No. 1638 C) of undried Illinois coal—Continued.

SECOND SERIES—10 GRAMS ON 4-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	0.0280	−0.28	25	50
5 minutes	.0380	− .38	....	....
15 minutes	.0605	.61	....	....
1½ hours	.1965	1.96	25	43
21 hours	− .2535	−2.54	24	36
24 hours	− .2140	−2.14	28	35
25 hours	+ .0575	+ .58	25	63
42 hours	+ .0130	+ .13	18	64
104 hours	− .0518	− .52	27	35
15 days	− .0622	.62	32	41
48 days	− .0725	− .72	32	55
Total loss in 72 days	....	9.06	....	....

THIRD SERIES—17.2 GRAMS IN OPEN, WIDE-MOUTHED 2-OUNCE BOTTLE.

10 minutes	−0.0025	−0.014	22	61
1¼ hours	.0115	− .067	....	....
3½ hours	.0260	.15	....	....
21 hours	− .0800	− .47	24	36
Stirred and reweighed	.0020	− .01	....	....
24 hours	− .0855	.50	28	36
Stirred with spoon	− .0020	− .01	....	....
26 hours	.0885	− .51	25	63
Stirred with spoon	.0015	− .01	....	....
42 hours	− .0625	− .36	18	64
Stirred with spoon	− .0010	.005	....	....
4 days	− .1190	− .70	27	35
Stirred with spoon	− .0005	− .003	....	....
15 days	− .3625	−2.11	32	41
Stirred with spoon	− .0000	− .000	....	....
48 days	− .0200	− .116	32	55
Total loss in 72 days	....	5.035	....	....

A second sample (No. 1638 E) of undried Illinois coal contained 11.89 per cent moisture, and being a duplicate of No. 1638 C, except that it was perhaps more finely pulverized, was also tested in a similar way, by spreading 1 gram on a 3-inch watch glass and 10 grams on a 3-inch watch glass, and by placing 14.5 grams in an open, wide-mouthed 2-ounce bottle. The changes occurring in these three samples are given in the following table:

Changes in moisture content of sample (No. 1638 E) of undried Illinois coal.

FIRST SERIES—1 GRAM ON 3-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0215	−2.15	25	50
5 minutes	− .0160	−1.60	....	....
20 minutes	− .0110	−1.10	....	....
1½ hours	− .0290	−2.90	25	43
20¾ hours	− .0055	−0.55	24	36
24½ hours	− .0063	−0.63	28	36
25 hours	+ .0143	+1.43	25	63
42 hours	+ .0060	+ .60	18	64
104 hours	− .0142	−1.42	27	35
15 days	+ .0025	+ .25	32	41
48 days	− .0173	−1.73	32	55
Total loss in 72 days	....	9.80	....	....

Changes in moisture content of sample (No. 1638 E) of undried Illinois coal—Continued.

SECOND SERIES—10 GRAMS ON 3-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0518	−0.52	25	50
5 minutes	− .0270	.27	....	....
15 minutes	− .0530	− .53	....	....
1¼ hours	− .2180	−2.18	25	43
21¼ hours	− .2000	−2.00	24	36
24¼ hours	− .1937	−1.94	28	36
25 hours	− .0692	+ .69	25	63
42 hours	.0095	+ .095	18	64
104 hours	− .0550	− .55	27	35
15 days	− .0590	− .59	32	41
48 days	− .0870	− .87	32	55
Total loss in 72 days	....	8.67	....	....

THIRD SERIES—11.5 GRAMS IN OPEN, WIDE-MOUTHED 2-OUNCE BOTTLE.

10 minutes	−0.003	−0.02	22	61
1¼ hours	− .0135	− .09	....	....
3¼ hours	− .0340	− .23	....	....
21 hours	− .0890	− .60	21	36
Stirred with spoon	− .0020	− .01	....	....
24 hours	− .0995	− .68	28	36
Stirred with spoon	− .0025	− .02	....	....
26 hours	− .0850	− .56	25	63
Stirred with spoon	− .0015	− .01	....	....
42 hours	− .0625	.42	18	64
Stirred with spoon	− .0010	− .01	....	....
104 hours	− .0875	− .60	27	35
Stirred with spoon	.0015	− .01	....	....
15 days	− .2538	−1.71	32	41
Stirred with spoon	− .0010	− .01	....	....
48 days	− .0500	− .35	32	55
Total loss in 72 days	....	5.33	....	....

Other experiments were likewise performed on a similar sample (No. 1639 C) of Illinois coal, which contained 4.12 per cent moisture, although the coarse sample had been well air-dried before the preparation of the fine sample. The changes in weight in the 1-gram sample spread on a watch glass, in the 10-gram sample spread on a watch glass, and in a portion (8.3 grams) allowed to stand exposed in an open, wide-mouthed 2-ounce bottle were as follows:

Changes in moisture content of sample (No. 1639 C) of well-dried Illinois coal.

FIRST SERIES—1 GRAM ON 4-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0093	−0.93	28	36
5 minutes	− .0025	.25	....	....
15 minutes	− .0015	.15	....	....
2¼ hours	+ .0045	+ .45	....	....
23 hours	+ .0135	+1.35	25	63
2 days	+ .0070	+ .70	18	64
4 days	− .0170	−1.70	27	35
14 days	+ .0060	+ 40	32	41
Total loss in 21 days	....	0.13	....	....

Changes in moisture content of sample (No. 1639 C) of well-dried Illinois coal—Continued.

SECOND SERIES—10 GRAMS ON 4-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory	
			Temperature.	Humidity.
	Grams.	*Per cent.*	°*C.*	*Per cent.*
5 minutes	−0.0190	−0.19	28	36
5 minutes	− .0120	− .12		
15 minutes	− .0175	− .175		
1 hour	− .0280	− .28		
23 hours	+ .1235	+1.24	25	63
2 days	+ .0195	+ .20	18	64
4 days	− .0580	− .58	27	35
14 days	− .0280	− .28	32	41
Total loss in 21 days		0.18		

THIRD SERIES—8.3 GRAMS IN OPEN, WIDE-MOUTHED 2-OUNCE BOTTLE.

10 minutes	+0.0015	+0.02	23	69
20 minutes	+ .0010	+ .01		
20 minutes	− .0000			
5¼ hours	+ .0080	+ .08	25	63
2 days	+ .0230	+ .29	18	64
Stirred	− .0000			
4 days	+ .0240	.29	27	35
14 days	− .0175	− .21	32	41
Stirred	− .0000	.00		
Total gain in 20 days		0.48		

An inspection of these results shows that in samples of fine coal prepared from coal not previously air dried the loss may be rapid, being in a 1-gram portion of undried sample over 2 per cent in five minutes and over 8 per cent in twenty-four hours. That samples kept in bottles may lose a considerable amount of moisture unless tightly stoppered is also shown by the results obtained from weighing the samples in an open bottle, the loss in twenty-four hours being nearly 0.7 per cent and in seventy-two hours almost 2 per cent. This loss continued until the total loss in twenty-four days was about 5 per cent. That the danger from losses in handling a fine sample which has been well air dried is not nearly so great is shown by the tests upon No. 1639 C. Upon the 1-gram portion of this sample the loss in five minutes was 0.93 per cent, but the additional loss afterwards was small, showing that the sample was not far from air dry under the existing conditions. In fact, under the conditions existing on the next afternoon the sample as ground was drier than air dry, as is shown by an increase of over 1 per cent in weight. That this sample was about air dry, under the average conditions existing, is furthermore shown by the results obtained on the sample exposed in an open bottle, where the sample at different times shows small losses and small gains in weight. The rapidity with which the 1-gram portion of this dried sample gave up the little moisture it possessed over and above the existing air-dry conditions shows the extreme sensitiveness of finely ground coal samples to changes in the moisture content of the air.

As might be expected, the rapidity of gain or loss is greatest in the 1-gram sample and least in the sample kept in an open bottle. A comparison of these losses after seventy-two days on the undried samples shows, however, that even in that time the loss on the 1-gram sample is decidedly in excess of that on the 10-gram sample, and about twice that on the sample in the open bottle. This result would lead to the inference that the change in weight is not due entirely to moisture losses, but is influenced more or less by oxidation changes. That such is the case is shown by the results of tests of the gain or loss in weight, from time to time, of fine samples kept in tightly stoppered bottles, moisture determinations being made at the same time to find out whether the amount of moisture present in the sample varies with the change in weight. These tests are described under "Alteration of weight of samples of coal when kept in a finely powdered state," pages 19–22.

COMPARISON OF EFFECTS OF DIFFERENT DRYING REAGENTS USED IN THE DESICCATORS EMPLOYED IN MOISTURE DETERMINATIONS.

In the determinations of moisture made during the Louisiana Purchase Exposition and during the earlier part of 1905 duplicate results often were not as close as was desirable. This lack of agreement was found to be due, in part at least, to the use of calcium chloride as a drying reagent in the desiccators in which the fine samples of coal were allowed to cool after drying at 105° C., as may be seen from inspection of the following table giving the values obtained over concentrated sulphuric acid, fused calcium chloride, and granular calcium chloride.

Certain values from samples allowed to stand overnight, which are marked with a star (*), were on different gram portions of the sample. The values given for the other determinations, weighed as soon as cooled and weighed after standing in the desiccator overnight, are on the same weighed-out portions of the sample, which, as soon as weighed the first time, were put back in the desiccator and allowed to stand until the next day and then again weighed. The values over sulphuric acid are, as a rule, about one-tenth of 1 per cent lower on the sample after standing overnight, but this result can probably be accounted for by the small amount of moisture which might be taken up by the sample during the time required for making the first weighing.

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Moisture determinations obtained by the use of different drying reagents.

Sample of coal.		Concentrated H_2SO_4.		$CaCl_2$, fused.		$CaCl_2$, granular.	
Laboratory number.	Field number.	1.[a]	2.[b]	1.[a]	2.[b]	1.[a]	2.[b]
1660	Illinois No. 11 B	3.46		3.42 3.38		3.38 3.40	
1786	Illinois No. 13	3.92				3.86	
1802	Illinois No. 11 D	6.34		6.26			
1801	Illinois No. 7 D	2.74				2.74	
1803	Illinois No. 13	7.62		7.46			
1804	....do	4.74		4.80			
1794	Alabama	1.38		1.18			
1798	Illinois No. 13	4.96				4.80	
1812	....do	3.56		3.46			
1817	Indian Territory	1.42				1.30	
1828	Indiana No. 8	3.62		3.46			
1835	Brazil	4.99	4.92			4.91	4.58
1837	Illinois No. 7 D	3.60	3.60	3.55	3.23		
1807	Indiana No. 4	4.94				4.88	
1808	Illinois No. 12	5.90				5.82	
1836	Illinois No. 13	2.76				2.70	
1838	Illinois No. 18					5.08	
1842	Illinois No. 7 D	1.06		1.02			
1843	Colorado					7.98	7.40
1845	Illinois No. 11 D			4.12	3.46		
1846	Illinois No. 7 D	6.98	6.88	6.90	6.36		
1855	Illinois No. 11 D	1.24	1.14			1.14	.94
1844	Indiana No. 4	3.60				3.56	
1741	Illinois No. 18			3.32	2.58*		
1743	Indian Territory			2.36	1.88*		
1745	....do			3.38	2.76*		
1753	Illinois No. 11			12.09	11.58*		

[a] Weighed as soon as cooled.
[b] Weighed after standing in desiccator overnight.

The values obtained over both granular and fused calcium chloride, where the sample was weighed as soon as cooled, are but little lower than the values obtained over sulphuric acid; but the values from the samples over calcium chloride when allowed to stand overnight are so decidedly lower as to show beyond a doubt the superiority of concentrated sulphuric acid over calcium chloride as a desiccating reagent for coal.

EFFECTS OF VARYING AMOUNTS OF SAMPLE AND OF DIFFERENCES IN DURATION OF HEATING ON RESULTS OBTAINED FOR MOISTURE.[a]

The following results were obtained on (1) a very finely ground sample of Illinois coal, and (2) a fine sample of Indiana coal. They show the loss in weight which occurred when the samples were dried for different times, in different amounts, and under different conditions. This change in weight represents not merely the loss of moisture, but includes any changes due to oxidation and other causes. These changes undoubtedly vary with the kind of coal and the condition of the sample.

[a] The official method for the determination of moisture is to heat 1 gram of the fine sample for one hour at 105° C. in a drying oven.

Moisture determinations on Illinois coal (percentages).

Details of treatment.	½-gram sample.	1-gram sample.	2-gram sample.
Loss after 15 minutes' heating at 100° to 107°	8.42	6.65	5.24
Additional loss after another 15 minutes' heating at 100° to 107°	.84	2.62	3.70
Total loss after 30 minutes' heating	9.26	9.27	8.94
Additional loss after heating another 30 minutes at 100° to 107°	.06	.16	.43
Total loss after 1 hour's heating	9.32	9.43	9.37
Gain in weight by standing uncovered 41 hours	3.68	3.68	3.55
Total loss after heating another 30 minutes	8.86	9.20	9.27
Gain in weight after standing 41 hours and reheating as compared with the value at the end of 1 hour's heating	.46	.23	.10

Moisture determinations on Indiana coal (percentages).

Details of treatment.	½-gram sample.	1-gram sample.	2-gram sample.	4-gram sample.
Loss after 30 minutes' heating at 105°	5.50	5.60 to 5.58	5.62 to 5.61	5.49
Loss after heating another 30 minutes at 105°	.04	.08 to .04	.07 to .02	.15
Total loss after 1 hour's heating	5.54	5.68 to 5.62	5.69 to 5.63	5.64
Gain in weight by standing uncovered 20 hours	3.41	3.43 to 3.35	3.41 to 3.35	3.34
Total loss after heating another hour at 105°	5.20	5.45 to 5.37	5.53 to 5.48	5.55
Gain in weight after 20 hours' standing and 1 hour's reheating compared with weight after first hour's heating	.34	.23 to .25	.16 to .15	.09
Gain in weight by standing uncovered 120 hours	3.06	3.12 to 2.95	3.15 to 3.11	3.12
Total loss after heating another hour at 105°	4.90	5.14 to 5.10	5.19 to 5.17	5.21
Gain in weight compared with weight after the first hour's heating	.64	.54 to .52	.50 to .46	.43
Gain in weight by standing uncovered 24 days	3.70	3.62 to 3.58	3.52 to 3.51	3.45
Total loss after another hour's heating at 105°	4.20	4.60 to 4.62	4.72 to 4.70	4.77
Gain in weight compared with weight after first hour's heating	1.34	1.08 to 1.00	.97 to .93	.87

These results show that practically all of the moisture is expelled from coals of these kinds during the first thirty minutes, and, furthermore, that there was an appreciable amount of oxidation in the sample during standing or from reheating. For short periods this oxidation value in these experiments was apparently a surface reaction, dependent on the surface exposure of the sample and not on the amount. The samples were all weighed out in porcelain crucibles of the same size, and the amount of sample directly exposed was practically the same in all. In this case the percentage effect of equal oxidation on the Illinois samples would be in the ratio of 4, 2, and 1. The gains actually determined at the end of 41 hours were 0.46, 0.23, and 0.10 per cent, respectively, which are very close to this ratio.

On the Indiana sample the gains for oxidation at the end of twenty hours were 0.34, 0.24, 0.15, and 0.09 per cent, respectively. At the end of twenty-four days the percentages of gain on the different amounts are more nearly the same, but the gain is still greatest on the ½-gram sample and least on the 4-gram sample, the gains on the four amounts taken being 1.34, 1.04, 0.95, and 0.87 per cent, respectively.

ALTERATION OF WEIGHT OF SAMPLES OF COAL WHEN KEPT IN A FINELY POWDERED STATE.

In order to investigate the question of the extent of alteration of the samples when kept in a finely powdered condition as prepared for analysis, portions of a number of such samples were put in weighed

bottles, which were securely closed with rubber stoppers. These bottles were kept in the laboratory and weighed from time to time. Moisture determinations were made on portions of the sample at the times of the weighings, allowance being made for the portions removed for this purpose. The following table gives the percentage of moisture originally present in the sample, the percentage of gain or loss in weight at the several weighings, and the time interval between the weighings; also the total time covered by the experiment:

Alteration of weight of finely powdered coal.

[Minus sign denotes loss.]

Sample of coal. Laboratory number.	Sample of coal. Field number.	Days between weighings.	Change in weight.	Moisture determination.
			Per cent.	*Per cent.*
1635	Illinois No. 9 A			5.10
		4	0.17	5.13
		20	.47	5.31
		42	.46	5.36
		25	.19	5.29
		172	.00	4.99
		124	-.33	4.38
		387	.96	-.72
1638 C	Illinois No. 9 B			12.34
		4	.16	12.58
		19	.45	12.12
		27	.22	12.03
		41	.23	11.79
		172	.00	11.62
		263	1.06	-.72
1638 E	do			11.89
		4	.17	11.97
		46	1.07	11.80
		41	.40	11.64
		191	.00	11.06
		282	1.64	-.83
1639	do			4.03
		23	.61	4.03
		42	.47	4.38
		34	.31	4.53
		163	.27	4.37
		127	-.12	4.23
		389	1.54	.20
1660	Illinois No. 11 B			3.25
		15	.40	3.26
		27	.42	3.47
		50	.43	3.89
		183	.10	3.60
		107	.00	3.57
		382	1.35	.32
1844	Indiana No. 4			3.58
		7	.22	3.79
		34	.48	3.90
		183	.53	3.87
		107	.14	3.63
		331	1.37	.05
1867	West Virginia No. 13			1.03
		24	.24	1.16
		191	.15	1.21
		108	.07	1.09
		323	.46	.06

Alteration of weight of finely powdered coal—Continued.

[Minus sign denotes loss.]

Laboratory number.	Sample of coal. Field number.	Days between weighings.	Change in weight.	Moisture determination.
			Per cent.	*Per cent.*
2062	Ohio No. 5			1.99
		9	.22	
		18	.22	
		149	.40	2.49
		108	.13	2.43
		284	.97	.44
2131	Wyoming No. 2			4.65
		2	.04	
		3	.06	
		24	.18	
		7	.10	
		43	.09	
		28	.00	
		55	.06	4.55
		107	.02	4.46
		269	.55	-.19
2243	North Dakota No. 3			26.64
		4	.05	
		3	.03	
		7	.08	
		43	.23	
		28	.07	
		55	.16	25.91
		107	.05	25.64
		247	.57	-1.00
2275	Wyoming No. 2 B			6.37
		2	.05	
		7	.05	
		43	.13	
		28	.02	
		55	.06	6.15
		135	.31	-.22
2278	Wyoming No. 3			12.59
		2	.09	
		7	.22	
		43	.68	
		28	.15	
		55	.38	11.97
		107	.26	11.81
		242	1.78	.78
2255	North Dakota No. 3			12.62
		2	.02	
		5	.17	
		43	.34	
		28	.15	
		56	.16	12.86
		134	.84	.24
2718	Texas No. 4			33.00
		6	.29	
		42	.24	
		3	.03	32.87
		51	.56	-.13
2828	Massachusetts peat			13.60
		8	.07	
		13	.09	
		3	.00	13.72
		103	-.72	13.16
		127	-.56	-.44

Without exception these samples all increased in weight upon standing. At the same time the moisture values usually decreased. The gain in weight is to be ascribed to oxidation, and the decrease in moisture either to actual loss or to fixation of a portion of the moisture present by the oxidation changes. If the moisture loss be considered as an actual escape of moisture from the sample, the total gain due to oxidation is equal to the observed gain plus an amount equal to this moisture loss. The table below gives the total oxidation changes considered on this basis, together with the original and final calorimeter determinations on some of the samples, also the loss in calorific value in excess of that due merely to changes in weight of the sample. For purposes of comparison the amounts of moisture, ash, and sulphur present in the sample are also given.

Determinations of oxidation, calorific value, moisture, ash, and sulphur.

[Minus sign denotes loss.]

Sample of coal.		Increase in weight due to oxidation.	Calorific value.			Moisture.	Ash.	Sulphur.
Laboratory number.	Field number.		Original.	Final.	Gain or loss above that accounted for by oxidation.			
		Per cent.	*Calories.*	*Calories.*	*Calories.*	*Per cent.*	*Per cent.*	*Per cent.*
1635	Illinois No. 9 A	1.68	....	....	....	4.99	11.80	4.43
1638C	Illinois No. 9 B	1.78	....	....	....	12.34	....	....
1638E	.....do	2.47	....	....	....	11.89	....	....
1639	.....do	1.34	....	....	....	4.03	11.48	4.40
1660	Illinois No. 11 B	1.03	....	....	....	3.25	12.38	2.62
1844	Indiana No. 4	1.32	6,426	6,265	−77	3.58	16.05	2.59
2828	Massachusetts peat	1.00	4 055	4,049	35	13.60	20.74	.58
2243	North Dakota No. 3	1.57	4,498	4,431	3	26.64	8.88	1.32
2255	.....do	.60	....	....	....	12.62	8.77	1.22
2062	Ohio No. 5	.53	7,501	7,375	−86	1.99	7.48	1.76
2718	Texas No. 4	.69	....	....	....	33.00	7.66	....
1867	West Virginia No. 13	.40	8,408	8,359	−17	1.03	2.40	.83
2131	Wyoming No. 2	.74	5,815	5,747	−26	4.64	21.77	4.22
2275	Wyoming No. 2 B	.53	....	....	....	6.37	19.69	4.09
2278	Wyoming No. 3	2.56	5,108	4,903	−75	12.59	17.20	6.86

The oxidation changes in every case are sufficiently large to be of practical importance, the smallest change—that in the Ohio No. 5 sample—being 0.53 per cent, while the Illinois No. 9 B sample showed a change of 2.47 per cent. The Wyoming No. 3 sample showed an increase of 2.56 per cent in weight and a decrease of 205 calories in heating value. The changes in weight correspond to a decrease in heating value of 144 calories, the final calorific value obtained being 75 calories lower than is accounted for by the changes in weight. Further results along these lines are desirable, but the values already obtained show very clearly that old samples of coal can not be regarded as representative of the original coal in composition or in calorific value.

DETERMINATIONS OF SPECIFIC GRAVITIES OF THE COALS.

Two determinations of specific gravity were made on a number of lumps about 1 inch in diameter. The first determination was made upon a number of specially selected lumps representing as clean coal as could be picked out, carefully avoiding portions contaminated with slate or pyrites; the second was made upon a number of lumps selected to represent the average quality of the coal as nearly as could be expected in pieces of this size. The determinations of each kind were made (in duplicate and sometimes in triplicate) with a large Nicholson's hydrometer designed for use with the coke samples and capable of handling 1,000 grams of coal. The following table gives the results on the two kinds of lumps. For ease of reference and for comparison the determinations of ash and sulphur on the car samples of each coal are also tabulated.

Determinations of ash, sulphur, and specific gravity.

Designation of coal sampled.	Car sample.		Specific gravity.	
	Ash.	Sulphur.	Selected lumps.	Average lumps.
Alabama No. 2 B	14.59	1.12	1.32	1.37
Alabama No. 3	14.36	.55	1.30	1.38
Alabama No. 4	12.92	1.08	1.28	1.32
Arkansas No. 7 A	11.69	2.02	1.32	1.44
Brazil	21.93	2.72	1.37	1.40
Illinois No. 19 B	9.36	.91	1.31	1.33
Illinois No. 23 A	11.53	4.41	1.22	1.26
Illinois No. 25	13.40	4.76	1.26	1.30
Illinois No. 26	12.09	3.51	1.22	1.31
Illinois No. 27	13.77	4.05	1.24	1.28
Indiana No. 5	10.88	4.27	1.28	1.42
Indiana No. 6	12.62	4.39	1.25	1.39
Indiana No. 7 A	9.21	3.74	1.27	1.40
Indiana No. 8	10.61	3.72	1.29	1.30
Indiana No. 9 A	10.30	3.27	1.25	1.36
Indiana No. 9 B	10.76	3.15	1.25	1.33
Indiana No. 10	8.57	3.83	1.24	1.29
Indiana No. 11	8.14	1.41	1.26	1.30
Indiana No. 12	11.65	3.87	1.26	1.32
Kansas No. 6	15.72	3.72	1.23	1.34
Kentucky No. 1 B	3.37	.88	1.27	1.40
Kentucky No. 5	3.70	.67	1.29	1.30
Kentucky No. 6	2.76	.57	1.27	1.28
Kentucky No. 7	9.48	3.60	1.31	1.44
Maryland No. 1	13.13	1.49	1.36	1.41
Missouri No. 6	11.74	5.60	1.21	1.36
New Mexico No. 3	16.67	.73	1.29	1.37
New Mexico No. 4 A	14.57	.61	1.30	1.39
New Mexico No. 5	14.57	.69	1.31	1.35
North Dakota No. 1 B	11.42	3.54	1.25	1.44
North Dakota No. 3	7.75	1.15	a 1.22	
Ohio No. 1	11.95	4.61	1.29	1.35
Ohio No. 2	11.33	4.02	1.31	1.36
Ohio No. 3	11.58	1.81	1.30	1.33
Ohio No. 4	9.12	3.47	1.30	1.39
Ohio No. 5	7.30	1.72	1.29	1.33
Ohio Nos. 6 A, 6 B	8.52	3.33	1.29	1.35
Ohio No. 7	6.37	2.16	1.30	1.34
Ohio No. 8 A	8.37	2.84	1.30	1.42
Ohio No. 9 A	8.29	3.15	1.29	1.31
Ohio No. 9 B	11.93	3.35	1.30	1.36
Pennsylvania No. 4	10.41	1.26	1.30	1.35
Pennsylvania No. 5 A	6.02	1.20	1.30	1.31
Pennsylvania No. 5 B	6.06	.88	1.28	1.33
Pennsylvania No. 6	13.00	1.95	1.30	1.33
Do	12.52	1.94	1.30	1.38
Pennsylvania No. 7 A, 7 B	12.47	2.08	1.33	1.41
Pennsylvania No. 8	6.63	.94	1.31	1.36
Pennsylvania No. 9	11.33	2.04	1.35	1.39

a No distinction made between clean or selected lumps and average lumps.

Determinations of ash, sulphur, and specific gravity—Continued.

Designation of coal sampled.	Car sample.		Specific gravity.	
	Ash.	Sulphur	Selected lumps.	Average lumps.
Pennsylvania No. 10	6.17	1.26	1.30	1.36
Tennessee No. 2	6.81	.98	1.28	1.33
Tennessee No. 3	7.05	.99	1.29	1.32
Tennessee No. 4	9.63	.98	1.29	1.37
Tennessee No. 6	14.43	.78	1.29	1.31
Tennessee No. 7 A	12.85	3.26	1.34	1.39
Tennessee No. 8 A	13.42	4.38	1.34	1.37
Tennessee No. 10	59.14	.21	1.35	....
Texas No. 3	7.88	.99	....	1.25
Texas No. 4	7.30	.51	....	1.26
Virginia No. 1 A	4.73	1.20	1.27	1.30
Virginia No. 1 B	5.01	1.11	1.27	1.34
Virginia No. 2 B	5.58	.92	1.28	1.37
Virginia No. 3	4.48	67	1.27	1.28
Virginia No. 4	4.33	.79	1.28	1.28
Washington No. 1 B	11.37	.72	1.28	1.33
Washington No. 2	12.26	.38	1.32	1.39
West Virginia No. 4 B	7.76	.81	1.31	1.35
West Virginia No. 13	3.91	.89	1.27	1.30
West Virginia No. 14	3.27	1.03	1.27	1.28
West Virginia No. 15	8.55	2.54	1.28	1.31
West Virginia No. 16 A	5.57	1.06	1.30	1.37
West Virginia No. 16 B	8.37	1.20	1.28	1.34
West Virginia No. 17	8.12	1.45	1.28	1.41
West Virginia No. 18	5.83	.67	1.30	1.34
West Virginia No. 19	5.01	89	1.26	1.38
West Virginia No. 20	8.03	1.38	1.27	1.34
West Virginia No. 21	4.85	1.32	1.28	1.34
Wyoming No. 2 B	20.79	4.03	1.31	1.37
Wyoming No. 3	16.70	6.66	1.23	1.40
Wyoming No. 4	6.77	.26	1.33	1.35
Wyoming No. 5	3.41	.81	1.26	1.30
Wyoming No. 6	3.12	.49	1.28	....

It is obvious from the foregoing table that the specific gravity of the lumps of coal is considerably affected by the amount of impurities contained. Even the selected lumps were not free from ash and sulphur, so that it is not possible to obtain the true specific gravity of the pure coal itself.

In order to further investigate the relation of impurities to specific gravity, five of the coals in the foregoing table were selected as representing the great diversity of character. These coals were separated first into sizes and then each size, except the dust, was further separated by "float-and-sink" tests upon heavy solutions, of 1.35 specific gravity calcium chloride and 1.45 and 1.65 specific gravity zinc chloride. The procedure in detail was as follows:

The coal, after crushing till it all passed a ½-inch screen, was sifted over a series of sieves—80 mesh, 40 mesh, 10 mesh, and 4 mesh. That passing the first two screens was designated "dust;" that passing the 10 mesh and retained on the 40 mesh was designated "fine;" that passing the 4 mesh and retained on the 10 mesh "medium," and that retained on the 4 mesh "coarse." The dust was not separated on the solution, but each of the remaining classes was then stirred in a solution of 1.35 specific gravity, and the floating coal was removed, washed, and air dried. That sinking in this solution was then washed, dried, weighed, and stirred in a solution of 1.45 specific gravity, and the floating coal treated as before; and the process was again repeated in a solution of

1.65 specific gravity with the coal that sank. Each product was washed, air dried, and analyzed.

The results are given in the following table. Column 1 gives the percentage that the amount of coal in each grade of fineness forms of the entire sample treated; column 2, the percentage that the amount of coal in each class separated by gravity forms of the amount in its grade of fineness, and column 3, the percentage that the amount of coal in each class forms of the entire sample. Column 4 gives the determination of the ash in each class, expressed as a percentage of the amount of coal in the class; column 5, this determination of the ash expressed as a percentage of the entire sample of coal, and columns 6 and 7 give the same percentages for the sulphur. The totals of the results for ash and sulphur, in columns 5 and 7, should obviously equal the ash and sulphur determinations, respectively, in the original coal, which are printed below them for purposes of comparison. The differences are due to unavoidable errors in the work and, in some cases, probably in part to the presence of sulphates extracted in washing.

Impurities in coal as related to different grades of fineness and classes of specific gravity.

NO. 2023, BRAZIL NO. 1.[a]

Grade and class of coal.	Mechanical distribution of coal.			Amount of ash in each class.		Amount of sulphur in each class.	
	Per cent of entire sample in each grade.	Amount in each class.		As per cent of coal in the class.	As per cent of entire sample of coal.	As per cent of coal in the class.	As per cent of entire sample of coal.
		Per cent of its own grade.	Per cent of entire sample.				
	1.	2.	3.	4.	5.	6.	7.
Dust {80	3.95	56.43	....	28.64	1.131	1.90	0.075
Dust {80 to 40	3.05	43.57	....	26.35	.804	1.60	.049
Sum	7.00	100.00	7.00				
Fine, 40 to 10	18.10	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	62.11	11.15	11.64	1.298	.61	.068
1.35 to 1.45	....	2.23	.40	15.33	.061	.84	.003
1.45 to 1.65	....	17.83	3.20	30.22	.967	.615	.020
Above 1.65	....	17.83	3.20	54.49	1.744	5.41	.173
Sum	....	100.00	17.95				
Medium, 10 to 4	30.45	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	55.53	17.55	13.90	2.439	.60	.105
1.35 to 1.45	....	3.64	1.15	23.38	.269	.59	.007
1.45 to 1.65	....	28.01	8.85	33.38	2.954	.55	.049
Above 1.65	....	12.82	4.05	55.08	2.231	8.92	.361
Sum	....	100.00	31.60				
Coarse, 4 to 2	44.60	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	45.10	21.20	17.33	3.674	.64	.136
1.35 to 1.45	....	3.19	1.50	26.52	.398	.50	.007
1.45 to 1.65	....	31.92	15.00	32.74	4.911	.66	.099
Above 1.65	....	19.79	9.30	59.08	5.494	21.24	1.975
Sum	....	100.00	47.00				
Total	100.15	....	103.55	....	28.375	....	3.127
Original sample	....	....	....	....	28.18	....	4.28

[a] Sp. gr. of average lumps, 1.40; of selected lumps, 1.37.

Impurities in coal as related to different grades of fineness, etc.—Continued.

NO. 2346, MARYLAND NO. 1.[a]

Grade and class of coal.	Mechanical distribution of coal.			Amount of ash in each class.		Amount of sulphur in each class.	
	Per cent of entire sample in each grade.	Amount in each class.		As per cent of coal in the class.	As per cent of entire sample of coal.	As per cent of coal in the class.	As per cent of entire sample of coal.
		Per cent of its own grade.	Per cent of entire sample.				
	1.	2.	3.	4.	5.	6.	7.
Dust {80	5.05	52.06	....	15.47	0.781	2.00	0.101
Dust {80 to 40	4.65	47.94	....	12.99	.604	1.55	.072
Sum	9.70	100.00	9.70				
Fine, 40 to 10	33.45	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	81.40	27.10	6.25	1.694	.92	.249
1.35 to 1.45	....	10.07	3.35	13.62	.456	1.25	.042
1.45 to 1.65	....	3.75	1.25	25.02	.313	2.21	.028
Above 1.65	....	4.78	1.60	61.48	.984	9.04	.145
Sum	....	100 00	33.30				
Medium, 10 to 4	41.95	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	63.60	26.65	5.57	1.484	.84	.224
1.35 to 1.45	....	25.54	10.70	13.77	1.473	1.21	.129
1.45 to 1.65	....	5.85	2.45	25.63	.628	2.36	.058
Above 1.65	....	5.01	2.10	57.63	1.210	8.14	.171
Sum	....	100.00	41.90				
Coarse, 4 to 2	14.70	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	39.15	5.75	6.45	.371	.84	.048
1.35 to 1.45	....	38.10	5.60	14.16	.793	1.07	.060
1.45 to 1.65	....	10.84	1.60	25.68	.411	2.48	.040
Above 1.65	....	11.91	1.75	55.90	978	7.28	.127
Sum	....	100.00	14.70				
Total	99.80	....	99.60	....	12.180	....	1.49
Original sample	....	....	....	....	12.53	....	1.51

NO. 2308, PENNSYLVANIA NO. 6.[b]

Grade and class of coal.	1.	2.	3.	4.	5.	6.	7.
Dust {80	5.50	55.85	....	14.74	0.811	2.36	0.130
Dust {80 to 40	4.35	44.15	....	12.35	.537	2.19	.095
Sum	9.85	100.00	9.85				
Fine, 40 to 10	20.40	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	88.36	17.85	6.44	1.149	1.10	.196
1.35 to 1.45	....	2.97	.60	17.55	.105	2.75	.016
1.45 to 1.65	....	1.98	.40	28.26	.113	4.04	.016
Above 1.65	....	6.69	1.35	67.45	.911	10.20	.138
Sum	....	100.00	20.20				
Medium, 10 to 4	29.75	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	81.38	24.25	6.15	1.491	1.10	.267
1.35 to 1.45	....	9.06	2.70	16.97	.458	2.39	.065
1.45 to 1.65	....	2.68	.80	29.70	.238	3.42	.027
Above 1.65	....	6.88	2.05	63.95	1.311	11.39	.233
Sum	....	100.00	29.80				
Coarse, 4 to 2	39.70	....	....	....	....	....	....
Specific gravity—							
Under 1.35	....	70.42	27.95	6.21	1.736	1.07	.299
1.35 to 1.45	....	13.86	5.50	16.37	.900	2.33	.128
1.45 to 1.65	....	4.78	1.90	29.57	.562	2.47	.047
Above 1.65	....	10.94	4.35	66.20	2.880	7.06	.307
Sum	....	100.00	39.70				
Total	99.70	....	99.55	....	13.202	....	1.964
Original sample	....	....	....	....	12.61	....	1.76

[a] Sp. gr. of average lumps, 1.41; of selected lumps, 1.36.
[b] Sp. gr. of average lumps, 1.33; of selected lumps, 1.30.

Impurities in coal as related to different grades of fineness, etc.—Continued.

NO. 2298, WEST VIRGINIA NO. 15.[a]

Grade and class of coal.	Mechanical distribution of coal.			Amount of ash in each class.		Amount of sulphur in each class.	
	Per cent of entire sample in each grade.	Amount in each class.					
		Per cent of its own grade.	Per cent of entire sample.	As per cent of coal in the class.	As per cent of entire sample of coal.	As per cent of coal in the class.	As per cent of entire sample of coal.
	1.	2.	3.	4.	5.	6.	7.
Dust {80	5.35	55.15	5.35	10.35	0.554	3.42	0.183
Dust {80 to 40	4.35	44.85	4.35	8.27	.360	3.10	.115
Sum	9.70	100.00	9.70				
Fine, 40 to 10	22.65						
Specific gravity—							
Under 1.35		92.68	20.90	4.39	.917	1.62	.338
1.35 to 1.45		1.33	.30	13.63	.041	6.37	.019
1.45 to 1.65		.89	.20	22.75	.046	10.10	.020
Above 1.65		5.10	1.15	57.78	.671	26.95	.310
Sum		100.00	22.55				
Medium, 10 to 4	33.20						
Specific gravity—							
Under 1.35		90.65	30.05	4.56	1.370	1.59	.478
1.35 to 1.45		3.77	1.25	13.40	.167	6.48	.081
1.45 to 1.65		1.81	.60	22.89	.137	10.25	.061
Above 1.65		3.77	1.25	53.03	.663	26.26	.328
Sum		100.00	33.15				
Coarse, 4 to 2	34.30						
Specific gravity—							
Under 1.35		86.30	29.60	5.40	1.597	1.73	.512
1.35 to 1.45		6.42	2.20	13.10	.288	6.40	.141
1.45 to 1.65		3.49	1.20	24.88	.298	7.40	.089
Above 1.65		3.79	1.30	66.15	.860	13.05	.171
Sum		100.00	34.30				
Total	99.85		99.70		7.969		2.846
Original sample					7.34		2.82

NO. 2278, WYOMING NO. 3.[b]

Grade and class of coal.	1.	2.	3.	4.	5.	6.	7.
Dust {80	2.05	54.62		23.45	0.481	8.89	0.182
Dust {80 to 40	1.70	45.38		19.43	.330	8.21	.139
Sum	3.75	100.00	3.75				
Fine, 40 to 10	11.50						
Specific gravity—							
Under 1.35		74.12	8.30	5.46	.453	4.91	.407
Above 1.35		25.88	2.90	47.51	1.378	14.43	.418
Sum		100.00	11.20				
Medium, 10 to 4	29.85						
Specific gravity—							
Under 1.35		77.03	22.65	5.54	1.255	4.72	1.069
Above 1.35		22.97	6.75	47.98	3.239	15.54	1.049
Sum		100.00	29.40				
Coarse, 4 to 2	54.85						
Specific gravity—							
Under 1.35		69.65	38.20	6.53	2.494	4.66	1.780
Above 1.35		30.35	16.65	50.03	8.330	18.04	3.004
Sum		100.00	54.85				
Total	99.95		99.20		17.960		8.048
Original sample					17.96		8.36

[a] Sp. gr. of average lumps, 1.31; of selected lumps, 1.28.
[b] Sp. gr. of average lumps, 1.40; of selected lumps, 1.28.

An examination of the figures in the foregoing table shows the very rapid increase in impurity of the coal with increase in specific gravity. The finer the coal is crushed the more complete would be the mechanical separation of the heavy impurities from the coal, but the behavior in this respect evidently varies greatly with different coals. In the Brazil coal the sulphur is nearly the same in all the coal under ½-inch size and below 1.65 specific gravity, while the ash increases both with size and with the specific gravity. In the Maryland coal both sulphur and ash increase with specific gravity, and apparently without very much reference to size of product. Practically the same is true of the Pennsylvania No. 6 coal and of the West Virginia coal. The record of the Wyoming coal is not sufficiently complete for comparison. In all but the Brazil coal there is a marked tendency to increase of ash and sulphur in the fine dust, suggesting that the impurities are liberated in crushing and are more brittle than the mass of the coal. Noticeably different compositions in ash and sulphur of the portions of the various coals below 1.35 specific gravity, may indicate either actual variations in the specific gravity of the coal proper or variations in the nature of the combination of the sulphur and mineral matter.

Further experiments along these lines seem very desirable.

LABORATORY METHODS OF DETERMINING ADAPTABILITY OF COALS TO IMPROVEMENT BY WASHING.

The laboratory method of testing consists in floating the sample upon solutions of different density and thereby separating the coal into portions of different specific gravity, the amounts of these portions being determined and each portion analyzed separately for ash and sulphur, as noted under the last heading. The samples used were crushed to one-half inch and finer before testing, and for convenience in handling were divided by sifting into two portions, one one-half inch to one-fortieth inch, the other one-fortieth inch and finer. On some of the earlier samples the division was made at one-twentieth inch. The solutions used for washing the samples were a calcium-chloride solution of 1.35 specific gravity and a zinc-chloride solution of 1.65 specific gravity. Solutions of 1.45 and 1.90 specific gravity were also used occasionally. The clean coal, low in ash, floats upon a solution of 1.35 specific gravity. Moderately high-ash coal sinks in a solution of this gravity, but floats upon a solution of 1.45 specific gravity. Coal very high in ash is heavier than 1.45, but floats upon a solution of about 1.65 specific gravity, while the slate and pyrites sink in solution of this gravity. The results obtained by washing the samples upon these different solutions and the analysis of the resultant products, together with the analysis of the original sample and the analysis of samples obtained from actual washing tests made at the washery connected with the fuel-testing plant upon 5- to 6-ton lots of

certain of the coals, are given in the tables of results below. As these laboratory samples were all crushed to one-half inch and finer before testing, these results do not necessarily show what might be done with the coal crushed to other sizes. They do, however, give an indication of the possible improvements which may be expected from washing.

The "one-fortieth inch and finer" portion of the sample was tested as follows: The sample was stirred up with water, and after settling for one minute the liquid was decanted off very closely and the remaining portion was dried, weighed, and analyzed. The loss on decantation indicates in a very general way the extent to which the coal breaks down into a fine powder upon handling or crushing, and is an indication of the amount of fine coal lost during washing. The particular crushing machinery used would, however, greatly affect the amount of fines produced in crushing. The analytical results on the portion remaining after decantation are in a general way an index to the way the impurities separate from the coal in crushing.

The interpretation of these results may perhaps be understood best by a consideration of the results derived from some particular sample, as Indiana No. 7 A. In this sample the ash and sulphur contents in the unwashed coal are, respectively, 9.03 and 3.75. The sample crushed to "½ inch to $\frac{1}{40}$ inch" was separated by sifting into 91.1 per cent coarse and 8.6 per cent fine. Considering the coarse portion: The part lighter than 1.35 specific gravity amounted to 86.7 per cent of the entire sample, and contained 6.69 per cent ash and 3.05 per cent sulphur. It is quite probable that in actual washing practice a large part of the "$\frac{1}{40}$ inch and finer" would be reduced in ash and sulphur contents to about the same percentage, which would indicate the possibility of improving this coal 2 per cent in ash and 0.7 per cent in sulphur, accompanied by a washing loss of about 10 per cent. The distribution of the ash and sulphur on the heavier portion is shown by the percentage results on the "1.35 to 1.65" portion and on the portion "Heavier than 1.65." The washery tests do not show so great an improvement in ash and sulphur as might be expected from the analysis of the portion "Lighter than 1.35," and a portion of the "1.35 to 1.65" specific gravity material evidently remained with the washed coal. However, washery tests upon such small lots of coal can not be expected to give the best results; also the possible improvement at ½-inch size is apt to be greater than can be obtained at 1¼-inch size, at which the sample was worked at the washery. The results of the laboratory tests indicate that the high sulphur and the comparatively high ash in the washed coal from the washery is not the fault of the washing, but is due to the combination in which the ash and sulphur occur, showing that a very low ash and sulphur product can not be obtained from this coal by washing. The laboratory tests do, how-

ever, indicate that under the best conditions of washing there would be some improvement, but not much, over the results obtained at the washery of the fuel-testing plant.

Determinations of ash and sulphur in coal samples variously treated.

ILLINOIS NO. 9 A.

[Unwashed coal—ash, 11.21; sulphur, 4.53.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
First series:					
¼ inch to $\frac{1}{16}$ inch	91.9				
Lighter than 1.35	75.2	6.08	3.16	4.57	2.38
1.35 to 1.65	12.1	21.04	4.80	2.55	.58
Heavier than 1.65	4.2	58.34	16.93	2.45	.71
$\frac{1}{16}$ inch and finer	9.0				
Very fine, decanted [a]	2.3			.26	.10
Remainder	5.6	13.88	4.20	.78	.24
				10.61	4.01
Second series:					
¼ inch to $\frac{1}{16}$ inch	91.9				
Lighter than 1.45	84.9	8.22	3.32	6.98	2.82
Heavier than 1.45	7.7	44.02	14.12	3.39	1.09
$\frac{1}{16}$ inch and finer	7.7				
Very fine, decanted [a]	2.4			.27	.11
Remainder	5.6	13.88	4.20	.78	.24
				11.42	4.26
Washed at 1¼-inch size:					
Sample No. 1		8.14	3.63		
No. 2		8.26	3.71		

ILLINOIS NO. 11 B.

[Unwashed coal—ash, 12.54; sulphur, 2.86.]

¼ inch to $\frac{1}{16}$ inch	80.1				
Lighter than 1.35	56.5	5.71	1.72	3.22	0.97
1.35 to 1.65	16.1	17.49	2.48	2.82	.40
Heavier than 1.65	5.7	58.42	11.91	3.33	.68
$\frac{1}{16}$ inch and finer	19.5				
Very fine, decanted [a]	5.8			.73	.17
Remainder	13.7	17.42	3.15	2.39	.43
				12.49	2.65

ILLINOIS NO. 19 B.

[Unwashed coal (boiler-test sample, No. 2044)—ash, 10.57; sulphur, 0.49.]

¼ inch to $\frac{1}{16}$ inch	92.8				
Lighter than 1.35	80.9	4.79	0.63	3.88	0.51
1.35 to 1.65	5.6	27.03	.52	1.51	.03
Heavier than 1.65	6.5	65.75	.29	4.28	.02
$\frac{1}{16}$ inch and finer	6.9				
Very fine, decanted [a]	3.5			.37	.02
Remainder	3.4	16.05	.60	.55	.02
				10.59	.60

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

INDIANA NO. 4.

[Unwashed coal (boiler-test sample, NO. 1892)—ash, 15.63; sulphur, 2.74.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to 1/20 inch	81.9				
Lighter than 1.35	61.8	5.89	1.82	3.66	1.12
1.35 to 1.65	11.9	17.50	3.54	2.10	.42
Heavier than 1.65	8.9	69.29	7.01	6.17	.62
1/20 inch and finer	17.5				
Very fine, decanted [a]	5.3			.83	.15
Remainder	12.2	23.83	2.84	2.88	.35
				15.64	2.66
Washed at 1¼-inch size:					
Sample No. 1		8.26	2.26		
No. 2		7.69	2.26		

INDIANA NO. 6.

[Unwashed coal (boiler-test sample, No. 1928)—ash, 13.54; sulphur, 4.83.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to 1/20 inch	76.1				
Lighter than 1.35	56.2	6.63	2.92	3.73	1.64
1.35 to 1.65	13.6	19.58	5.54	2.66	.75
Heavier than 1.65	6.7	54.89	13.75	3.68	.91
1/20 inch and finer	23.2				
Very fine, decanted [a]	6.9			.93	.33
Remainder	16.3	17.10	5.19	2.79	.85
				13.79	4.48
Washed at 1¼-inch size:					
Sample No. 1		10.34	3.67		
No. 2		10.98	3.94		
No. 3		10.06	3.73		

INDIANA NO. 7 A.

[Unwashed coal (boiler-test sample, No. 1939)—ash, 9.03; sulphur, 3.75.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to 1/20 inch	91.1				
Lighter than 1.35	86.7	6.69	3.05	5.80	2.64
1.35 to 1.65	3.6	26.23	4.39	.94	.16
Heavier than 1.65	3.4	55.84	23.48	1.90	.80
1/20 inch and finer	8.6				
Very fine, decanted [a]	5.4			.49	.20
Remainder	3.2	17.13	4.48	.55	.14
				9.68	3.94
Washed at 1¼-inch size:					
Sample No. 1		8.94	3.33		
No. 2		8.18	3.36		

INDIANA NO. 9 B.

[Unwashed coal (boiler-test sample, No. 2035)—ash, 10.98; sulphur, 3.02.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to 1/20 inch	78.4				
Lighter than 1.35	64.2	8.04	2.30	5.16	1.48
1.35 to 1.65	7.3	25.90	4.60	1.89	.33
Heavier than 1.65	3.2	60.75	16.70	1.94	.52
1/20 inch and finer	21.3				
Very fine, decanted [a]	8.8			.97	.26
Remainder	12.5	19.87	4.24	2.48	.53
				12.44	3.12
Washed at 1¼-inch size:					
Sample No. 1		9.22	2.91		
No. 2		8.54	2.69		

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

INDIANA NO. 11.

[Unwashed coal (boiler-test sample, No. 2421)—ash, 8.60; sulphur, 1.61.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
½ inch to 1/20 inch	80.9				
Lighter than 1.35	72.4	6.10	1.22	4.42	0.88
1.35 to 1.65	4.9	25.90	2.78	1.27	.14
Heavier than 1.65	3.4	54.34	10.14	1.85	.34
1/20 inch and finer	18.7				
Very fine, decanted [a]	9.7			.83	.16
Remainder	9.0	13.69	2.30	1.25	.21
				9.62	1.73

KENTUCKY NO. 6.

[Unwashed coal (boiler-test sample, No. 2662)—ash, 3.15; sulphur, 0.44.]

	Portion.	Ash.	Sulphur.	Compared with original sample: Ash.	Compared with original sample: Sulphur.
½ inch to 1/20 inch	89.8				
Lighter than 1.35	88.4	2.27	0.56	2.01	0.50
1.35 to 1.65	.6	27.30	.71	.15	.00
Heavier than 1.65	.6	71.61	.85	.43	.01
1/20 inch and finer	9.8				
Very fine, decanted [a]	6.0			.19	.03
Remainder	3.9	6.85	.70	.27	.03
				3.05	.57

MISSOURI NO. 5.

[Unwashed (boiler-test sample, No. 2892)—ash, 16.94; sulphur, 5.60.]

	Portion.	Ash.	Sulphur.	Compared with original sample: Ash.	Compared with original sample: Sulphur.
½ inch to 1/20 inch	91.5				
Lighter than 1.35	74.7	6.86	3.17	5.12	2.37
1.35 to 1.65	8.4	23.13	6.97	1.94	.59
Heavier than 1.65	9.4	55.85	16.28	5.25	1.53
1/20 inch and finer	8.2				
Very fine, decanted [a]	3.3			.57	.19
Remainder	4.9	25.30	6.73	1.24	.33
				14.12	5.01
Washed at 1½-inch size:					
Sample No. 1		10.28	4.10		
No. 2		10.12	3.94		

MISSOURI NO. 6.

[Unwashed coal (boiler-test sample, No. 2927)—ash, 11.67; sulphur, 5.52.]

	Portion.	Ash.	Sulphur.	Compared with original sample: Ash.	Compared with original sample: Sulphur.
½ inch to 1/20 inch	89.2				
Lighter than 1.35	79.6	6.96	3.69	5.54	2.94
1.35 to 1.65	7.0	21.08	8.33	1.48	.58
Heavier than 1.65	6.1	46.89	20.81	2.86	1.27
1/20 inch and finer	10.4				
Very fine, decanted [a]	2.0			.23	.11
Remainder	8.4	16.55	6.66	1.39	.56
				11.50	5.46

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

OHIO NO. 1.

[Unwashed coal (boiler-test sample, No. 2136)—ash, 16.91; sulphur, 5.34.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to $\frac{1}{20}$ inch	87.0				
Lighter than 1.35	57.5	5.97	2.91	3.43	1.67
1.35 to 1.65	16.8	18.91	5.87	3.18	.98
Heavier than 1.65	7.3	54.85	15.01	3.97	1.10
$\frac{1}{20}$ inch and finer	12.9				
Very fine, decanted [a]	7.3			1.23	.39
Remainder	5.7	29.56	7.04	1.69	.40
				13.50	4.54
Washed at 1¼-inch size:					
Sample No. 1		9.20	3.98		

OHIO NO. 5.

[Unwashed coal (boiler-test sample, No. 2101)—ash, 8.02; sulphur, 1.65.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch and $\frac{1}{20}$ inch	90.8				
Lighter than 1.35	78.1	4.77	1.39	3.73	1.09
1.35 to 1.65	7.5	17.33	2.53	1.30	.19
Heavier than 1.65	3.4	69.67	3.72	2.37	.13
$\frac{1}{20}$ inch and finer	8.9				
Very fine, decanted [a]	6.4			.51	.10
Remainder	2.6	12.70	2.74	.33	.07
				8.24	1.58

PENNSYLVANIA NO. 8.

[Unwashed coal (boiler-test sample, No. 2446)—ash, 6.33; sulphur, 0.89.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to $\frac{1}{20}$ inch	78.5				
Lighter than 1.35	71.0	5.02	0.58	3.56	0.41
1.35 to 1.65	4.8	21.19	1.49	1.02	.07
Heavier than 1.65	1.6	51.98	8.36	.83	.13
$\frac{1}{20}$ inch and finer	21.2				
Very fine, decanted [a]	12.6			.80	.11
Remainder	8.6	7.51	1.10	.65	.09
				6.86	.81

PENNSYLVANIA NOS. 7 A AND 7 B.

[Unwashed coal (boiler-test sample, No. 2182)—ash, 11.36; sulphur, 1.68.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
½ inch to $\frac{1}{20}$ inch	90.6				
Lighter than 1.35	73.5	8.81	1.40	6.48	1.03
1.35 to 1.65	14.6	23.12	2.03	3.38	.30
Heavier than 1.65	1.1	43.65	9.71	.48	.11
$\frac{1}{20}$ inch and finer	9.0				
Very fine, decanted [a]	7.4			.84	.13
Remainder	1.7	12.53	3.59	.21	.06
				11.39	1.63
Washed at 1¼-inch size:					
Sample No. 1		10.62	1.63		
No. 2		11.36	1.68		

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

PENNSYLVANIA NO. 10.

[Unwashed coal (boiler-test sample, No. 2373)—ash, 6.37; sulphur, 1.35.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
¼ inch to 1/40 inch	87.0	....	....	....	....
Lighter than 1.35	78.5	4.50	1.07	3.53	0.85
1.35 to 1.65	5.6	13.15	1.84	.75	.10
Heavier than 1.65	1.9	62.70	8.70	1.19	.17
1/40 inch and finer	12.7	....	....	....	....
Very fine, decanted [a]	7.6	....	....	.48	.11
Remainder	5.0	9.49	2.27	.48	.11
				6.43	1.34

TENNESSEE NO. 6.

[Unwashed coal (boiler-test sample, No. 3102)—ash, 14.86; sulphur, 0.80.]

	Portion.	Ash.	Sulphur.	Compared with original sample: Ash.	Compared with original sample: Sulphur.
¼ inch to 1/40 inch	93.8	....	....	....	....
Lighter than 1.35	71.5	3.42	0.67	2.45	0.47
1.35 to 1.65	7.7	20.64	1.18	1.59	.09
Heavier than 1.65	14.0	70.99	2.74	9.94	.38
1/40 inch and finer	5.9	....	....	....	....
Very fine, decanted [a]	2.7	....	....	.40	.02
Remainder	3.3	22.75	1.08	.75	.04
				15.13	1.00

VIRGINIA NO. 4.

[Unwashed coal (boiler-test sample, No. 2533)—ash, 4.02; sulphur, 0.45.]

	Portion.	Ash.	Sulphur.	Compared with original sample: Ash.	Compared with original sample: Sulphur.
¼ inch to 1/40 inch	92.8	....	....	....	....
Lighter than 1.35	88.3	1.93	0.48	1.70	0.41
1.35 to 1.65	1.3	15.91	.95	.20	.01
Heavier than 1.65	2.6	72.22	.92	1.877	.02
1/40 inch and finer	6.8	....	....	....	....
Very fine, decanted [a]	4.6	....	....	.18	.02
Remainder	2.3	10.24	.77	.24	.02
				4.19	.48

VIRGINIA NO. 2.

[Unwashed coal (boiler-test sample, No. 2557)—ash, 6.58: sulphur, 0.83.]

	Portion.	Ash.	Sulphur.	Compared with original sample: Ash.	Compared with original sample: Sulphur.
¼ inch to 1/20 inch	82.6	....	....	....	....
Lighter than 1.35	71.2	2.74	0.69	1.95	0.49
1.35 to 1.65	9.0	16.57	1.35	1.49	.12
Heavier than 1.65	1.3	60.02	9.65	.78	.13
1/20 inch and finer	17.1	....	....	....	....
Very fine, decanted [a]	12.6	....	....	.82	.10
Remainder	4.6	12.33	1.23	.57	.06
				5.61	.90
Washed at 1¼-inch size:					
Sample No. 1	....	4.15	.92	....	....
No. 2	....	4.02	.95	....	....
No. 3	....	4.55	.86	....	....

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

WEST VIRGINIA NO. 13.

[Unwashed coal (boiler-test sample, No. 2058)—ash, 3.93; sulphur, 0.96.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to $\frac{1}{16}$ inch	93.6				
Lighter than 1.35	89.1	2.41	0.83	2.15	0.74
1.35 to 1.65	2.2	20.72	1.27	.46	.03
Heavier than 1.65	1.7	70.16	2.59	1.19	.04
$\frac{1}{16}$ inch and finer	6.1				
Very fine, decanted[a]	3.6			.14	.04
Remainder	2.5	9.64	1.08	.24	.03
				4.18	.88

WEST VIRGINIA NO. 14.

[Unwashed coal (boiler-test sample, No. 2052)—ash, 2.27; sulphur, 1.07.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to $\frac{1}{16}$ inch	88.6				
Lighter than 1.35	84.4	1.52	0.88	1.28	0.74
1.35 to 1.65	1.0	14.52	2.11	.15	.02
Heavier than 1.65	1.0	58.60	13.45	.59	.13
$\frac{1}{16}$ inch and finer	11.1				
Very fine, decanted[a]	7.7			.17	.08
Remainder	3.4	7.10	1.89	.24	.07
				2.43	1.04

WEST VIRGINIA NO. 18.

[Unwashed coal (boiler-test sample, No. 2607)—ash, 6.21; sulphur, 0.67.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to $\frac{1}{16}$ inch	91.0				
Lighter than 1.35	86.0	4.88	0.68	4.20	0.59
1.35 to 1.65	3.0	22.81	.50	.68	.02
Heavier than 1.65	1.0	62.55	.57	.63	.01
$\frac{1}{16}$ inch and finer	8.6				
Very fine, decanted[a]	6.1			.38	.04
Remainder	2.5	7.97	.83	.20	.02
				6.09	.68

WYOMING NO. 2 B.

[Unwashed coal (boiler-test sample, No. 2164)—ash, 21.38; sulphur, 4.41.]

	Portion.	Ash.	Sulphur.	Compared with original sample. Ash.	Compared with original sample. Sulphur.
¼ inch to $\frac{1}{16}$ inch	94.0				
Lighter than 1.35	62.1	10.85	4.34	6.77	2.70
1.35 to 1.65	21.4	31.84	3.27	6.81	.70
Heavier than 1.65	12.1	64.30	6.48	7.78	.78
$\frac{1}{16}$ inch and finer	5.9				
Very fine, decanted[a]	3.3			.71	.15
Remainder	2.6	31.45	4.41	.82	.11
				22.89	4.44

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

SPECIAL TEST ON REFUSE FROM A WASHING.

[Original refuse—ash, 17.50; sulphur, 1.71.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
¼ inch to $\frac{1}{40}$ inch	85.2				
Lighter than 1.35	15.0	12.23	0.88	1.83	0.13
1.35 to 1.65	17.7	28.13	.76	4.98	.13
Heavier than 1.65	51.4	64.88	1.79	33.35	.92
$\frac{1}{40}$ inch and finer	14.5				
Very fine, decanted[a]	3.0			1.43	.05
Remainder	11.6	33.27	1.48	3.83	.17
				45.42	1.40

[a] Estimated from results on original refuse.

VOLATILE MATTER IN COALS AND LIGNITES.[a]

The official method of determining volatile matter, recommended by the committee on coal analysis appointed by the American Chemical Society, is as follows:

> Place 1 gram of fresh, undried, powdered coal in a platinum crucible weighing 20 or 30 grams and having a tightly fitting cover. Heat over the full flame of a Bunsen burner for seven minutes. The crucible should be supported on a platinum triangle, with the bottom 6 to 8 centimeters above the top of the burner. The flame should be fully 20 centimeters high when burning free, and the determination should be made in a place free from draughts. The upper surface of the cover should burn clear, but the under surface should remain covered with carbon. To find "volatile combustible matter," substract the per cent of moisture from the loss found here.

This method has been used regularly in the volatile determinations made in the laboratory, the only modification being that the flame is protected from air currents by inclosing the apparatus in a cylindrical asbestos shield 15 centimeters long and 7 centimeters in diameter, the platinum triangle being located 3 centimeters below the top of the shield. The use of the shield gives more uniformity in the heat treatment, with a corresponding greater uniformity of results.

In most coals the routine results obtained in the laboratory have checked to within less than 0.3 or 0.4 per cent; occasionally a sample has given trouble, and the variation between duplicates, without any apparent reason, was as great as 1 per cent. On some lignites it has been found impossible to obtain close duplicates, and on a few samples the official method gives very inaccurate determinations—as may be shown by the following results obtained in the laboratory upon two different samples, Nos. 2734 and 2764, of Texas No. 3 lignite, which differed only in the amount of moisture remaining in the air-dried sample, and perhaps in the fineness of grinding:

[a] By permission of Dr. J. A. Holmes, in charge, and the director of the laboratory, the results of this investigation of the volatile matter was published by Prof. E. E. Somermeier as a paper in the Journal of the American Chemical Society, August, 1906.

Laboratory analyses on samples 2734 and 2764 of Texas No. 3 lignite.

Constituent.	Samples. 2734. 1.	2764. 2.	3.
Moisture	9.88	20.24	20.24
Volatile matter	36.17	58.48	35.42
Fixed carbon	43.65	10.85	33.91
Ash	10.30	10.43	10.43
Sulphur	1.30	1.03	1.03

This great difference in the fixed-carbon results shown in columns 1 and 2 could not be accidental, as all of the determinations on both samples were duplicated. A series of determinations was begun, to learn, if possible, the cause of this great variation. The two following causes were suspected, both of which were found to be partly responsible for the difference: (1) Mechanical loss due to the throwing out of solid particles by the too rapid expulsion of the volatile matter. The possibility of loss from this source is mentioned in the report of the committee of the American Chemical Society, but the results of their experiments are negative. (2) A different breaking down of the hydrocarbon compounds when expelled under different conditions and in the presence of variable amounts of moisture.

The results of Mr. N. M. Austin's preliminary treatment of tne sample with a low heat and then with the application of the full flame of the Bunsen burner gives higher results in fixed carbon than where the full flame of the Bunsen burner is applied from the beginning. The proximate analysis of sample 2764, giving the unusual results, which was finally reported by the laboratory, is shown in column 3.

A series of seven results by the official method gave for volatile matter on this sample an average of 62.5 per cent, with a variation between high and low results of over 12 per cent. Three results of volatile matter on this sample made after previous expulsion of the moisture at 105° C. gave average volatile matter 39.6 per cent, with a variation between high and low results of 5.9 per cent. Preliminary treatment by driving off the moisture and most of the volatile matter at a low heat was then tried, the flame of the Bunsen burner being turned down to 10 centimeters and the crucible gradually heated. The application of the heat was regulated by holding the burner in the hand and heating in such a way as to expel the moisture slowly and gradually smoke off most of the volatile matter, the volatile matter escaping freely enough during the last minute of this preliminary heating to burn with a small flame around the edge of the crucible cover. Two results with five minutes of preliminary heating and then seven minutes over the full flame of the Bunsen burner gave an average in volatile matter of 35.08 per cent, the variation between the two results being 0.23 per cent. Two results with three minutes' pre-

liminary heating and seven minutes over the full flame of the Bunsen burner gave an average of 35.6 per cent, with a variation of 0.75 per cent between results. A result obtained by four minutes of preliminary heating and then seven minutes over the full flame gave 35.42 per cent. The difference in results obtained by the three-, four-, and five-minute preliminary treatment is small, and in all subsequent experimental tests the time of the preliminary heating was four minutes. To determine the mechanical losses and difference in volatile compounds given off, a number of ash determinations were made after the driving off of the volatile matter by the official method and after driving off the volatile matter in connection with the preliminary heating. The results of volatile matter and ash on three determinations by the official method and on two determinations by the modified method of four minutes of preliminary heating and then seven minutes over the full flame are as follows:

Determinations of volatile matter by two methods.

Constituent.	Official method.			Modified method.	
	1.	2.	3.	4.	5.
Volatile matter	66.72	67.47	54.82	36.06	36.65
Ash	4.30	4.38	[a] 7.25	11.16	11.15

[a] This result is possibly explained by the fact that this sample stood for two hours in the crucible after weighing out, and a considerable amount of the moisture content may have escaped before the sample was treated for the determination of the volatile matter.

That mechanical losses occurred during the rapid evolution of the volatile matter by the official method was also indicated by the shower of solid carbon particles driven off as sparks during the first few minutes, while with the preliminary heating these sparks were nearly or entirely absent. The average volatile matter on the first two determinations was 67.1 per cent, the average ash 4.34 per cent. The average volatile matter on the two results by the modified method was 36.35 per cent, ash 11.15 per cent. The moisture in the sample determined at this time was 19.78, giving fixed carbon 32.72 per cent. The difference in the ash results on the two pairs is 6.81 per cent, or the part of the ash driven off mechanically by the regular method is 6.81 ÷ 11.15, or 61 per cent. Taking this portion of the fixed-carbon result by the modified method gives 20 per cent as the amount of fixed carbon expelled mechanically in the first determinations. The results by the official method after making this correction, and also after taking the correct ash value, are shown in column 1 of the table below.

After making this correction for mechanical losses the difference in the fixed carbon by the two processes is still 10.75 per cent, which difference must be due to the difference in the breaking down of the hydrocarbon compounds by the different heat treatment. The ash

from the third result by the official method was 7.25 per cent, or the loss of ash 3.9 per cent. Correction for fixed carbon mechanically carried off is accordingly 3.9÷11.15, or 35 per cent. This portion of the fixed carbon as shown by the modified method gives 11.4 per cent as the amount of fixed carbon expelled mechanically. The result, after making the fixed-carbon and ash corrections, is shown in column 2 of the following table:

Corrected determinations by the official method.

Constituent.	Corrected results. 1.	2.
Moisture	19.78	19.78
Volatile matter	47.10	43.42
Fixed carbon	21 97	25.65
Ash	11.15	11.15
	100.00	100.00

The difference in this case in fixed carbon, due to the different heat treatment, is 7.07 per cent.

This particular sample was very finely ground. To find out how much the difference in result was due to the fineness of grinding a duplicate portion of the same sample was ground down till it passed a 40-mesh sieve. The results of duplicates by the official method and by the modified method are shown in the next table. The proximate analysis of the first sample by the modified method is shown in column 2. The correction for fixed carbon to be applied to the result of the official method is 0.95÷11.20, or 8.5 per cent of the fixed-carbon result of the modified method, which is 2.9 per cent. The results by the official method, after correcting for mechanical loss of fixed carbon and ash, are shown in column 1. The difference in fixed carbon between the two methods, due to different heat treatment, is 3.45 per cent. These rest show, at least for lignites, that the fineness of the sample has an important effect. Upon a second sample of lignite, similar to the first except that it contained more moisture (30.45 per cent), the average results by the modified process are as tabulated in column 4. A comparison of the results in volatile matter and ash by the official method shows that the correction to be applied to the fixed carbon and ash for mechanical loss is 2.71÷10.83. These corrections, as applied to the results obtained by the official method, are shown in column 3.

Determinations on sample ground to pass a 40-mesh sieve.

Constituent.	First sample.		Second sample.	
	Official method.	Modified method.	Official method.	Modified method.
	1.	2.	3.	4.
Volatile matter	42.07	35.72	44.40	30.97
Ash	10.25	11.20	8.12	10.83
Loss in ash	.95	....	2.71	....
Proximate analysis;				
Moisture	[a] 19.35	19.35	[a] 30.45	30.45
Volatile matter	[a] 39.17	35.72	[a] 37.43	30.97
Fixed carbon	[a] 30.28	33.73	[a] 21.29	27.75
Ash	[a] 11.20	11.20	[a] 10.83	10.83
	100.00	100.00	100.00	100.00

[a] After correcting for mechanical loss of fixed carbon and ash, the difference in the fixed-carbon results between the two samples, due to different heat treatment, is 6.46 per cent.

To test the effect of the fineness of grinding upon the determination of the volatile matter in ordinary bituminous coal, a sample of coal, Kentucky No. 1 C, containing 2 per cent moisture, 5.7 per cent ash, and 0.9 per cent sulphur, was still further reduced in ash content by floating on a calcium-chloride solution of 1.32 specific gravity. The lighter portion was then thoroughly air dried and separated by sifting into five sizes, and proximate analyses of the parts were made by the official method, with the following results:

Determinations for volatile matter on Kentucky No. 1 C coal.

Constituent.	Sizes of separation by sifting.				
	$\frac{1}{4}$ to $\frac{1}{10}$	$\frac{1}{10}$ to $\frac{1}{20}$	$\frac{1}{20}$ to $\frac{1}{40}$	$\frac{1}{40}$ to $\frac{1}{80}$	$\frac{1}{80}$ and finer.
Moisture	1.15	1.45	1.70	1.90	2.05
Volatile matter	39.05	38.80	38.55	38.05	35.54
Fixed carbon	58.20	58.55	58.35	58.40	59.66
Ash	1.60	1.20	1.40	1.65	2.75

By the modified process with four minutes of preliminary heating the result in volatile matter on the "$\frac{1}{20}$ to $\frac{1}{40}$" size was 33.75 per cent and on the "$\frac{1}{80}$ and finer," 32.85 per cent.

The results in volatile matter on these different sizes are somewhat higher on the coarse samples. However, the different ash contents of the different sizes indicate that the sizing had to a degree separated the coal into somewhat different varieties, as the higher ash content of the finer sample would not in itself be sufficient to account for the lower volatile results. In order to see whether the difference was due to the fineness of grinding or difference in the coals, a portion of the "$\frac{1}{20}$ to $\frac{1}{40}$" sample was ground down in an agate mortar and the volatile matter determined on this fine portion. The average of several results was 37.6 per cent, as against 38.55 per cent on the coarse sample.

From this series of results it appears, at least in low-moisture bituminous coals, that the finer ground samples give somewhat lower

volatile matter than the coarser samples, probably due to the more complete sintering together of the fine samples upon heating, with the consequent effect upon the giving off of the volatile matter.

In order to find out how much effect different heat treatment has on different fuels, a series of samples was selected ranging from anthracite to peat, most of the samples used in the tests having been previously more or less completely air dried so as to permit of better handling in the laboratory. Determinations for volatile matter were made in duplicate by the regular official method and by the modified method with four minutes' preliminary heating. The proximate analyses of the samples with the volatile matter determined by the official method are shown in columns 1 to 5 of the next table; the results for volatile matter by the preliminary heating are given in column 6; and the differences in volatile matter by the two methods are given in column 7. The determinations for moisture were all made in accordance with the official method, by weighing out a separate sample. The same is true of the determinations for ash, with the exception that upon two or three of the lignite samples and one of the Pennsylvania samples the results for ash are those obtained after the determination of the volatile matter by the modified process. These particular samples and results are all specifically mentioned elsewhere (p. 42).

Effect of different heat treatment on determination of volatile matter.

Fuel treated.	Proximate analysis (official method).					Volatile matter (modified method.)	Difference.
	Moisture.	Volatile matter.	Fixed carbon.	Ash.	Sulphur.		
	1.	2.	3.	4.	5.	6.	7.
Colorado anthracite	2.80	5.05	77.55	14.60	0.60	4.90	0.15
Arkansas	.83	12.47	72.05	14.65	2.14	12.37	.10
Pennsylvania	.90	17.35	74.92	6.83	.97	16.07	1.28
Do	1.05	33.10	53.30	12.55	1.76	30.35	2.75
Kentucky	2.99	37.51	56.68	2.82	.58	34.78	2.73
Indiana	4.20	37.70	45.65	12.45	4.13	34.67	3.03
Washington	6.65	35.87	44.57	12.91	.68	34.25	1.62
Indiana	8.40	34.40	48.72	8.48	1.47	32.00	2.40
North Dakota lignite	11.65	45.58	32.97	9.80	1.04	40.17	5.41
Illinois	12.40	32.18	42.82	12.60	1.30	30.12	2.06
Texas lignite (fine)	19.78	62.50	6.57	11.15	1.03	[a] 35.42	27.08
Texas lignite (40-mesh duplicate)	19.35	42.07	27.38	11.20	....	35.72	6.35
Texas lignite (not air dried)	30.45	44.40	15.42	9.73	....	30.97	13.43
Massachusetts peat	13.25	49.80	16.21	20.74	.58	47.92	1.88

[a] Two determinations upon the fine sample of Texas lignite made by heating for four minutes over a flame 5 centimeters high and then seven minutes over the full flame (25 cm.) gave 35.47 per cent volatile matter—almost an exact check upon the result obtained by the four-minute preliminary heating with a 10-centimeter flame regulated by holding burner in the hand.

With the exception of the anthracite and semianthracite samples, the results by the preliminary heating, as compared with those by the official method, all show a considerably less amount of volatile matter and a correspondingly greater amount of fixed carbon. In the case of the lignites, the greater volatile matter by the official method, as has been shown, is partly due to mechanical losses.

In order to see if mechanical losses might account for the differences on the bituminous coals, determinations for the ash after the determination of the volatile matter were made on one of the Pennsylvania samples. The average results for ash on the samples by the two methods are: Official method, 12.56; preliminary heating, 12.53. These results indicate no mechanical loss whatever, and in none of the samples except the lignites were visible solid carbon particles driven off in the form of sparks, and the differences must be ascribed to the different breaking down of the hydrocarbon compounds by the difference in heat treatment.

Comparisons of the results of volatile matter on a great number of samples differing from one another in moisture content indicate that the presence of loosely held moisture in the sample causes a higher volatile result. In order to obtain more definite data on this question, three samples low in moisture and representing widely different kinds of coal were selected for a series of determinations. The effect of loosely held moisture upon the determinations for volatile matter in each of these samples was determined by adding definite amounts of water to the sample after weighing out. The water was thoroughly mixed with the sample by means of a fine platinum wire and the volatile determination then made in the usual manner according to the official method. The first sample selected was a sample of Pennsylvania coal. The proximate analysis of the air-dried sample and the results for volatile matter determined in the presence of additional moisture are shown in the next table. Air-dried samples of Illinois coal and Arkansas lignite were treated in the same way, with the results also shown in the table.

Determinations of volatile matter (percentages) showing effect of loosely held moisture.

Fuel treated.	Proximate analysis (official method).					Volatile-matter determinations in the presence of stated amounts of added moisture.					
	Moisture.	Volatile matter.	Fixed carbon.	Ash.	Sulphur.	0.03 gram.	0.05 gram.	0.1 gram.	0.15 gram.	0.2 gram.	0.3 gram.
Pennsylvania coal	1.05	33.00	53.30	12.55	1.75	....	33.60	33.70	33.80	34.10	33.90
Illinois coal	2.35	39.35	41.65	13.65	......	39.60	39.30	40.00	40.05	39.75	....
Arkansas lignite	10.85	38.50	31.40	19.25	.83	....	40.35	41.20	40.90	44.90	....

Without exception these results show that the presence of loosely held moisture in the sample increases the value obtained for the volatile combustible matter. The average increase for the Pennsylvania sample is about 0.7 per cent. On the Illinois sample the increase for volatile matter is 0.4 per cent. On the Arkansas lignite the increase is 3.3 per cent.

To see what effect this loosely held moisture might have on the volatile determinations where the sample was first subjected to four

minutes' preliminary heating over a low flame, determinations were made upon these samples with and without additional moisture, with the following results:

Determinations of volatile matter (percentages) after four minutes' preliminary heating, showing effect of loosely held moisture.

Fuel treated.	Volatile-matter determinations (by modified method) in the presence of stated amounts of added moisture.			
	No moisture added.	0.15 gram.	0.2 gram.	0.3 gram.
Pennsylvania coal	30.35	....	....	31.65
Illinois coal	34.85	36.10	....	....
Arkansas lignite	36.90	....	37.40	....

These results show that even with a gradual preliminary heating the presence of loosely held moisture increases the value of the volatile determinations, the difference in some of the samples being as great as the difference by the official method; from which it appears that the rapid application of heat sufficient to drive off this moisture results in a reaction between the water vapor and the carbon or hydrocarbons in the coal.

The results of the foregoing experiments and tests show that the value obtained for volatile matter in coal is affected to an important degree: (1) By the method of heating the sample, (2) by the fineness of pulverization, and (3) by the amount of loosely held moisture present. In bituminous coals these differences do not exceed 3 or 4 per cent, and appear to be entirely due to a different breaking up of the hydrocarbon compounds under the different conditions of heat treatment, fineness of sample, and amount of moisture present. In the case of lignites, where the difference may be as high as 25 per cent, this difference is largely due to the mechanical loss in the sample during the rapid expulsion of the volatile matter.

In the routine work of the laboratory in making the determinations of volatile matter the official method is at present used for ordinary bituminous coals, while lignites or other coals with more than 10 per cent moisture are heated for four minutes at a low temperature and then for seven minutes over the full flame of the Bunsen burner.

INDEX.

CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 323.]

The publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists can be had on application.

Most of the above publications can be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they can be obtained, free of charge (except classes 2, 7, and 8), on application.

2. A certain number are delivered to Senators and Representatives in Congress for distribution.

3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they can be had at prices slightly above cost.

4. Copies of all Government publications are furnished to the principal public libraries in the large cities throughout the United States, where they can be consulted by those interested.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports, Q, Fuels; R, Structural materials. This paper is the fifty-second in Series E, and the fourth in Series Q, the complete lists of which follow (PP=Professional Paper; B=Bulletin):

SERIES E, CHEMISTRY AND PHYSICS.

B 9. Report of work done in the Washington laboratory during the fiscal year 1883-84, by F. W. Clarke and T. M. Chatard. 1884. 40 pp. (Out of stock.)

B 14. Electrical and magnetic properties of the iron carburets, by Carl Barus and Vincent Strouhal. 1885. 238 pp. (Out of stock.)

B 27. Report of work done in the Division of Chemistry and Physics, mainly during the year 1884-85. 1886. 80 pp.

B 32. Lists and analyses of the mineral springs of the United States (a preliminary study), by Albert C. Peale. 1886. 235 pp. (Out of stock.)

B 35. Physical properties of the iron carburets, by Carl Barus and Vencent Strouhal. 1886. 62 pp.

B 36. Subsidence of fine solid particles in liquids, by Carl Barus. 1886. 58 pp. (Out of stock.)

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Correspondence should be addressed to

THE DIRECTOR,

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WASHINGTON, D. C.

SEPTEMBER, 1907.

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DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, DIRECTOR

THE SAN FRANCISCO EARTHQUAKE AND FIRE OF APRIL 18, 1906

AND THEIR EFFECTS ON STRUCTURES AND STRUCTURAL MATERIALS

REPORTS BY

GROVE KARL GILBERT, RICHARD LEWIS HUMPHREY, JOHN STEPHEN SEWELL, AND FRANK SOULÉ

WITH PREFACE BY

JOSEPH AUSTIN HOLMES
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CONTENTS.

ILLUSTRATIONS.

(All the plates will be found at the end of the bulletin.)

PREFACE.

By Joseph A. Holmes.

Immediately after the San Francisco earthquake and fire of April 18, 1906, it was decided to arrange for an investigation of their effects on buildings and materials of construction. Accordingly, on April 19 Richard L. Humphrey was sent to San Francisco for this purpose, as secretary of the National Advisory Board on Fuels and Structural Materials and representing the structural materials division of the United States Geological Survey. At the request of the President, Capt. John Stephen Sewell, Corps of Engineers, United States Army, was sent to San Francisco on a similar errand by the War Department under order of April 23, 1906. Frank Soulé, dean of the college of civil engineering of the University of California, was asked late in the fall of 1906 to prepare a report on the general earthquake and fire conditions. G. K. Gilbert, of the United States Geological Survey, also a member of the California earthquake investigation commission, who was near San Francisco at the time of the disaster, was asked to prepare a brief special report on the phenomena of the earthquake.

Mr. Gilbert has brought into his paper only the salient features and results of the earthquake, for the reason that the subject is being treated more fully in the report of the California earthquake investigation commission.

Mr. Humphrey, who during the last two years has had charge of the structural materials laboratories of the United States Geological Survey, has had many years' experience in the investigation of structural materials, especially with regard to their fire-resisting qualities.

Before going to San Francisco Captain Sewell had studied carefully the effects of fire on buildings and materials, especially as indicated by the results of the conflagration at Baltimore in 1904.

Professor Soulé has had the advantage not only of a large experience, but also of being thoroughly familiar with the conditions in San Francisco prior to the earthquake and fire, and of being on the ground during their occurrence. He has had subsequently every opportunity for studying, at first hand and in great detail, the effects of both the earthquake and the fire.

The investigations of these three engineers were conducted independently, and their reports have been prepared without collaboration. Under these circumstances there are necessarily some differences of opinion as to matters of detail, but as to the more important features the writers are in hearty accord. About four hundred illustrations were submitted with the original reports; many of these do not appear with the printed reports because their use would have involved duplication, but wherever a view given by one author was rejected because of its similarity to a view by another author showing the same engineering features, a reference to the accepted view has been inserted. The legend appended to each illustration indicates whether the original view was actually taken by the author or was procured from another source.

Persons interested in this subject are advised not only to read each of these papers, but also to consult a number of other important papers on this subject which have appeared in the different technical journals and the proceedings of technical societies during the last several months. (See list at end of bulletin, pp. 159–161.)

THE SAN FRANCISCO EARTHQUAKE AND FIRE OF APRIL 18, 1906, AND THEIR EFFECTS ON STRUCTURES AND STRUCTURAL MATERIALS.

By G. K. GILBERT, R. L. HUMPHREY, J. S. SEWELL, and FRANK SOULÉ.

THE EARTHQUAKE AS A NATURAL PHENOMENON.

By G. K. GILBERT.

INTRODUCTION.

The investigations to which the San Francisco earthquake has given rise are of two classes—the study of the natural phenomena constituting or associated with the earthquake, and the study of the relations of the San Francisco earthquake and future earthquakes to human activities.

The principal studies of the earthquake as a natural phenomenon are under the direction of the California earthquake investigation commission, which was appointed by the governor of the State three days after the occurrence of the shock. The human or economic aspects of the subject have been studied chiefly by engineers and architects, of whom a number have acted in private capacity, while others have acted as the representatives of governmental or private organizations. In many of the architectural studies the earthquake and fire have been considered together, as the destructive effects of these two sources of danger were closely associated in the San Francisco disaster.

This volume is devoted to certain economic aspects of the subject, and the present chapter on natural phenomena of the earthquake selects those features which seem contributory to an understanding of the papers which follow. A fuller account of the earthquake may be found in the preliminary report of the State commission

above referred to; and a monographic report is to be expected when the labors of this commission shall have been completed.[a]

An earthquake is a jar occasioned by some violent rupture. Sometimes the rupture results from an explosion, but more commonly from the sudden breaking of rock under strain. The strain may be caused by the rising of lava in a volcano or by the forces that make mountain ranges and continents. The San Francisco earthquake of April 18, 1906, had its origin in a rupture associated with mountain-making forces. A rupture of this sort may be a mere pulling apart of the rocks so as to make a crack, but examples of that simple type are comparatively rare. The great majority of ruptures include not only the making of a crack but the relative movement or sliding of the rock masses on the two sides of the crack; that is to say, instead of a mere fracture there is a geologic fault. After a fault has been made its walls slowly become cemented or welded together; but for a long time it remains a plane of weakness, so that subsequent strains are apt to be relieved by renewed slipping on the same plane of rupture, and hundreds of earthquakes may thus originate in the same place.

A faulting may occur far beneath the surface and be known only through the resulting earthquake; but some of the quake-causing ruptures extend to the surface, and thus become visible. The New Madrid and Charleston earthquakes are examples of those having deep-seated origins; the shocks at Inyo and San Francisco, of those whose causative faults reached the surface of the ground.

The San Francisco earthquake had its origin, wholly or chiefly, in a new slipping on the plane of an old fault. The trend of the fault is northwest and southeast, and it is known through a distance of several hundred miles. Visible evidence of fresh slipping—a surface trace, to be described presently—does not appear through its whole extent, but has been traced from San Juan at the south to Point Arena at the north (fig. 1), a distance of about 180 miles. Because the earthquake was severe in Priest Valley, 60 miles southeast of San Juan, it is thought that subterranean slipping on the old fault plane extended beyond San Juan. At Point Arena the visible fault trace passes under the ocean, and the line of its trend does not again touch the coast, so that its northwestern course and extent are in doubt. A fault trace which appears at Point Delgada, 75 miles to the north, may be part of its continuation or may represent a separate fracture. In a general way the intensity of the shock was greatest near the

[a] The California earthquake investigation commission is composed of Andrew C. Lawson (chairman), A. O. Leuschner (secretary), G. K. Gilbert, H. F. Reid, J. C. Branner, George Davidson, Charles Burkhalter, and W. W. Campbell. Its work is organized under three committees—a committee on isoseismals, A. C. Lawson, chairman; a committee on coseismals, A. O. Leuschner, chairman, and a committee on the geophysics of the earthquake, H. F. Reid, chairman.

fault trace and diminished with distance therefrom; but to this rule there are important exceptions, and it has been noted especially

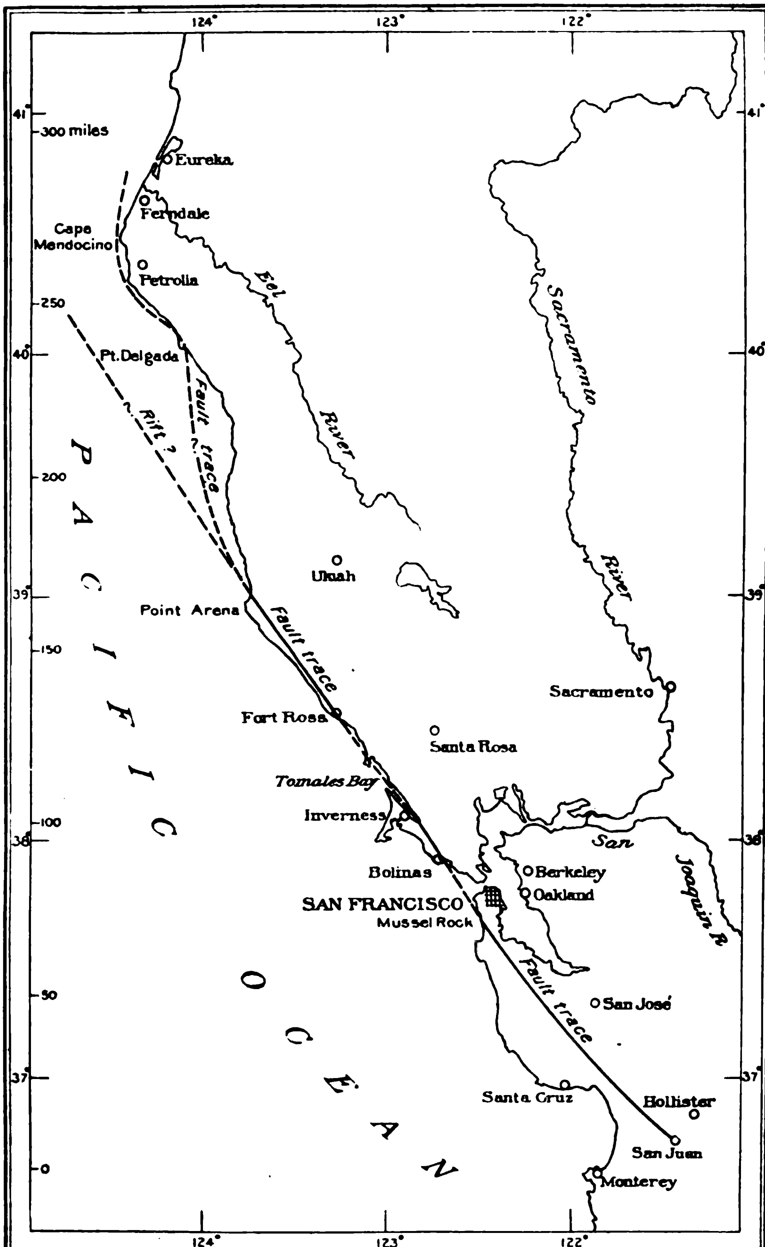

FIG. 1.—Map of the fault trace. Broken lines indicate alternative hypotheses as to its extension north of Point Arena.

that an area of high intensity coincided approximately with the Santa Rosa Valley, which trends northwestward, parallel to the main

fault. As the ridges of the neighboring Coast Range have the same northwesterly trend, it is thought probable that a subterranean slipping here occurred on a fault associated with the valley. In that case the geologic event causing the earthquake included coincident or nearly coincident yielding on more than one fault plane of the Coast Range system, and various other peculiarities in the distribution of intensity may be ascribed to local faulting.

The region of high intensity, to which most of the destruction was limited, is a belt 20 to 40 miles wide, extending from the mouth of Eel River at the northwest to Priest Valley at the southeast (fig. 1). This belt includes the surface expression of the principal fault—a feature distinctively known as the fault trace—a large number of cracks, and many local and superficial dislocations of soil and rock variously characterized as landslides and slumps.

THE FAULT TRACE.

The plane of the earthquake-causing fault, where it appears at the surface, is approximately vertical. The movement which took place along this plane was approximately horizontal.

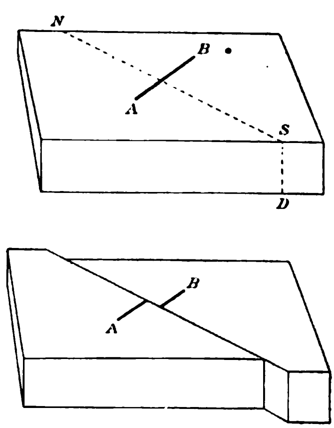

FIG. 2.—Diagrams illustrating the nature of the earthquake-making fault.

As the statement of these relations is sometimes found confusing, they are here illustrated diagrammatically. The upper diagram in fig. 2 represents a rectangular block as if cut from the land, the thickness being 25 feet, the length east and west (right to left) 150 feet, and the width 100 feet. The dotted line NS indicates the surface outcrop of the old fault plane, trending northwest and southeast, this plane cutting the face of the block in the vertical line SD. AB stands for any straight line on the surface of the land—such as would be defined by a road, a fence, or a row of trees—crossing the fault outcrop at right angles. The lower diagram represents the same

rectangular block after the earthquake, its two parts dislocated by sliding horizontally along the fault plane, and the line AB made discontinuous by an offset.

To return, now, from the ideal to the actual, the sides and bottom of the earth block disappear. The depth to which the fault penetrates is indefinite and unknown, and so is the extent of the lands on either side affected by the displacement. For nearly 200 miles there is a fracture on the face of the land, and everything traversed by the fracture is dislocated, the part on the southwest side having apparently moved toward the northwest and the part on the northeast side having apparently moved toward the southeast. The total horizontal offset ranges in general from 2 to 16 feet, but at one place, affected by abnormal conditions, reaches 20 feet (Pl. I, *A*). The effect is also shown by a redwood tree (Pl. II), which was situated at a place where the displacement was slight. The average offset is 10 to 12 feet. Associated with the horizontal dislocation are vertical dislocations of minor and variable amount. This line of fracture, with the associated dislocation, is the surface expression of the fault which occurred on April 18, 1906. It is the visible trace of the fault across the surface of the land, and in the following pages will be called the "fault trace."[a]

The fault trace itself is in some places inconspicuous, as in the flat meadow represented in Pl. I, *B*, where one might readily walk across it without noticing that the ground had been disturbed. Its ordinary phase, however, includes a disruption of the ground suggestive of a huge furrow, consisting of a zone, between rough walls of earth, in which the ground is splintered and the fragments are dislocated and twisted. This phase is shown in Pl. III. In many places the fault trace sends branching cracks into bordering land, and locally its effect in dislocation is divided among parallel branches.

The views of the fault trace given in Pl. VII represent it at a point not far from the head of Tomales Bay, where it traverses a hillside having a general slope toward the southwest. In the upper view we look toward the northwest; in the lower, toward the south-southeast. The horizontal displacement is here about 16 feet, the ground at the left, in each view, having moved from us, and the

[a] In the case of an earthquake fault with important vertical displacement the surface expression is a small cliff or scarp, and to such a feature the name "fault scarp" has been given; but this name does not serve to characterize the feature produced by the horizontal displacement of April 18, 1906. In default of an appropriate and established name the geologists who first traced the feature made tentative use of "furrow" and "rift;" and the word rift was employed in the preliminary report of the California commission, in a popular article by the present writer, and probably in other places. The commission, however, in giving more deliberate attention to terminology, has determined to reserve the word rift for a meaning more in consonance with earlier geologic usage and to substitute "fault trace" for the surface expression of the fault. The present paper conforms to the nomenclature accepted by the commission.

ground at the right toward us. There is also a vertical displacement, the ground on the southwest side having been relatively lifted 1 or 2 feet, and the expression of the vertical change is exaggerated in the lower view by the relation of the horizontal change to the local slope of the hillside. There is nothing in the pictures to show the amount or even the direction of the horizontal displacement, but measurements were made at neighboring points where the fault trace intersects a road, a trail, and a small gully. The nature of the evidence as to displacement is illustrated by Pl. I, *B*, which shows a dislocated fence. The locality is on the farm of E. R. Strain, near the head of Bolinas Lagoon, and the camera was directed toward the northeast—at right angles to the trend of the fault trace. The main branch of the fault trace (which is here divided) crosses the foreground from left to right, touching the dissevered ends of the fence, but the shear is at this point so smooth that its surface trace is concealed by the grass. The fence, which before the earthquake was straight and continuous, was broken across and offset to the distance of 8½ feet.

Between Point Arena and Fort Ross the course of the fault trace (see fig. 1, p. 3) is approximately parallel to the coast, passing to the east of all the coastal towns. From Fort Ross to the head of Tomales Bay it traverses the water, except at Bodega Bay and Preston Point, where for short distances it crosses the land. It again enters the water at Bolinas Lagoon, passing several miles outside the Golden Gate, and returning to the land at Mussel Rock, whence it follows a nearly direct course to San Juan. It does not touch any large town, but passes within a mile of Manchester, Plantation post-office, Fort Ross, Bodega, Inverness, Point Reyes station, Olema, Woodville, Bolinas, Woodside, Portola, Wrights, Chittenden, and San Juan.

On the east and west sides of the fault trace, respectively, the right-line distances to various places are as follows:

Distances from the fault trace to near-by prominent points.

EAST SIDE.	Miles.
Ukiah	26
Cloverdale	22
Healdsburg	20
Santa Rosa	19
Freestone	8
San Rafael	9
Sonoma	25
Petaluma	15
Martinez	29
Berkeley	19
Oakland	17
San Francisco—city hall	9
EAST SIDE—continued.	
San Francisco—Cliff House	3
San Mateo	4
Stanford University	5
San Jose	13
WEST SIDE.	
Point Reyes light-house	11
Halfmoon Bay	6
Pescadero	10
Santa Cruz	12
Salinas	13

CRACKS.

All through the area of high intensity cracks were made, and these were specially numerous near the fault trace. The cracks were also more numerous in soft alluvium than in hard ground, but the number which deeply penetrated the bed rock was large. Perhaps this feature is better expressed by saying that the bed rock was generally and profoundly shattered, but without important dislocation except on the old fault plane. The wide prevalence of shattering is shown by the derangement of the underground circulation of water. In every farming district within the main earthquake belt persons familiar with the springs noted changes in the flow of water, ranging from moderate diminution or increase to complete stoppage or to the breaking out of new springs. In some places the derangements were temporary only, but more commonly a permanent change was reported.

At the surface the cracks had great variety of expression. Some were barely perceptible as partings; others gaped so widely that one might look down them several yards. Some were mere pullings apart; others showed small differential movements of the nature of faulting. Some were solitary; others, especially those exhibiting faulting, were in groups. Some straggled and branched irregularly; others were nearly straight for hundreds of feet. Theoretically, some cracks were primary as regards the earthquake and others secondary; that is to say, some were caused directly by the preexistent stresses which produced the main fault and others were caused by the waves constituting the earthquake.

Pl. IV shows two types of secondary cracks. In *A* the cracks are crooked and without faulting. They traverse tidal mud near the head of Bolinas Lagoon and are near the main branch of the fault trace, which follows the base of the bluff seen at the right. The cracks seen in *B* are in Bolinas, within half a mile of the supposed position of the fault trace. The greater part of the village lies in a narrow valley dividing a plateau. The valley floor is of alluvium, the surface of which curves upward at the sides. As a result of the earthquake the alluvium settled somewhat toward the middle of the valley, thus forming along the bases of the hills a system of cracks associated with faulting.

DISLOCATIONS OF SURFACE MATERIAL.

The district most strongly affected by the earthquake is one in which landslips are normally of frequent occurrence. On many hill slopes were masses of earth or rock, the descent of which was sure to take place whenever conditions became favorable. The shaking of

the earth on the morning of April 18, 1906, supplied the lacking factor, and they were all loosened at once. In the simplest case, a poised rock toppled over and rolled down a slope. In other cases adhesion was overcome, with resultant sliding. In yet others strains occasioned by the sapping of cliffs were reinforced by kinetic strains and cohesion was overcome, with resultant fracture. Elsewhere an unconsolidated formation, even though in a dry condition, was made to flow by simple agitation. Hillside bogs and other bodies of wet earth lost coherence and flowed as mud. Slips of this character grade into those of wet alluvium or "made ground" resting upon gentle slopes—ground which under ordinary conditions flows or creeps at an almost imperceptible rate, but which by shaking was made to move several feet or yards in a few seconds. The filled districts of San Francisco afford several examples, and two of these are illustrated by Pls. V and VI, *B*. The view shown in Pl. V is northwestward on Ninth street, near Brannan. Before the earthquake the car tracks and curb line were straight and approximately level, and this condition was not disturbed on the relatively firm ground shown in the distance. In the nearer part of the view the street crosses a tract of made ground created by filling a valley tributary to a narrow tidal inlet called Mission Creek. The descent of this valley was southwestward, and the made ground flowed in that direction, carrying street and buildings with it. In taking the photograph reproduced in Pl. VI, *B*, the camera stood on ground made by the filling of Mission Lagoon, an expansion of Mission Creek, and was pointed northward, commanding a portion of Howard street. The made ground here flowed northeastward and the buckling of street-car tracks was caused by its motion. Where the same earth flow crossed Valencia street the horizontal movement amounted to 6 feet.

In the various cases of dislocation enumerated the motive force appeared to be gravity, and the apparent function of the earthquake was to initiate movement by overcoming equilibrium, adhesion, or cohesion, or else to increase mobility by agitation, and thereby temporarily convert a quasi solid into a quasi liquid. While I do not doubt that this explanation is ordinarily adequate, there is at least one dislocation of surface material for which it is inadequate, and this raises the question whether in various other instances it may not require qualification. I refer to an extensive shifting of mud on the bottom of Tomales Bay. At the head of the bay and thence for a distance of several miles northwestward the soft mud was moved bodily westward. It not only descended from the northeast shore, so as to cause deeper water, but ascended toward the southwest shore, creating a broad shoal (Pl. VII). The horizontal change of position near the southwest shore was in places more than 25 feet, and

the vertical change as much as 2 feet. As the ascending movement can not be ascribed to gravity, it must be referred to the earthquake, even though the way in which the earth waves produced the effect is not evident. The locality is adjacent to the fault trace, the position of which is along the bottom of the bay, east of the shoal.

The illustrations may require a few words of explanation. The upper view of Pl. VII looks northward from the southwest shore of the bay. Tide being low, the newly formed shoal or mud bank is broadly exposed, but the receding tide has left a lane of water to mark the separation of the mud bank from the firmer ground that withstood the quaking. Immediately after the earthquake the mud was rigid, as in the tract shown in Pl. VIII, A; but before the view of Pl. VII, A, was taken (April 28, 1906) the surface had been largely smoothed by the action of wind waves. A single ridge which escaped that action appears at the left in the upper view of Pl. VII and in the foreground of the lower view.

A permanent disturbance of the ground also resulted in many instances from compacting. Just as sand or grain that has been poured into a measure can be made by shaking to settle down and occupy less space, so various loose formations, and especially artificial fillings, were shaken together by the earthquake and the ground surface lowered. In such compacting the particles making up the aggregate are readjusted so as to fit more closely together and the voids are reduced. In dry formations compacted by the earthquake the reduction of voids was opposed only by the elasticity of the contained air. In wet formations it encountered the effectual resistance of the contained water, and could be accomplished only by the extravasation of some of the water. Ordinarily it was impossible to measure the settling due to compacting, or even to determine its occurrence as a phenomenon independent of ground flow, but it was clearly seen in various localities in San Francisco where those parts of graded streets which retained their simple shapes and straight lines served as reference planes for neighboring parts that were disturbed. (Compare the distance and foreground of Pl. V. Another example of the effect on the filled-in land in this part of the city is shown in Pl. VI, A, a view of Dore street between Bryant and Brannan streets. The settling of the soft ground caused the street to drop at least 5 feet at this place.)

The only notable water waves generated by the shock were in Tomales Bay, where a group of waves estimated to be 6 or 8 feet high came to the northeast shore. The automatic tide gage at the Presidio showed a depression of about 4 inches, with subsequent oscillations of similar amount. Water was spilled from tanks, etc., and in at least one place was thrown from a pool out on the land.

MOTIONS CONSTITUTING THE EARTHQUAKE.

The earthquake occurred between 10 and 15 minutes after 5 o'clock a. m., standard time of the one hundred and twentieth meridian. As time was consumed in the propagation of the shocks, the moment of beginning at any place depended in part on the distance of the place from the zone in which the disturbance originated. As this zone was hundreds of miles in extent it is probable that the time of beginning was not the same at all points along it. For similar reasons the character and sequence of the motions constituting the earthquake were not the same at any two localities, and the differences in the vicinity of the zone of origin may have been very great. In and near San Francisco the principal part had a duration of about one minute; it was preceded by comparatively faint tremors for several seconds, and it was followed by minor tremors. During the stronger part the motion was chiefly in horizontal directions and oscillatory, but its rhythm was irregular in period and emphasis. On firm ground in the same region the range of motion is believed to have been more than 2 inches, but was not measured, there being no seismograph capable of recording it. On soft ground the range of oscillatory motion may have been several times greater, and it was also greater in the immediate vicinity of the fault trace.

The following paragraphs present my conception of the essential character of the motions constituting the earthquake in the region of its destructive intensity. In the endeavor to make a brief and clear statement the conception is expressed somewhat badly, with little reference to the various uncertainties of fact and theory by which it is actually qualified.

The earthquake fault has a length of 300 miles, possibly 400. Nothing is known of its depth. It coincides with a plane of earlier faulting, on portions of which there have been movements within a few decades. The fact of recurrence on the same plane shows that the rock faces in contact had not become welded, so that the molecular force which there resisted motion was less than the cohesion of solid rock and may have been little stronger than adhesion. A tract of the crust including the fault plane had come to be affected by a system of slowly increasing shearing strains, and the associated stresses were the forces directly causing the fault. When the stress component coincident with the fault plane at some point became greater than the adhesion (or cohesion) a local slipping took place. This caused a redistribution of strains and stresses, the local relief of strain being followed by increase of strain and stress in all adjoining tracts of the fault plane, with the result that the adhesion was overcome in those tracts and the area of incipient faulting thereby enlarged. Thus from the initial tract the lesion was propagated as a sort of wave through all the fault plane.

At the initial tract a small movement sufficed to relieve the local strain, and the motion was then arrested by friction, but the movement was renewed by reaction from other tracts, and it alternately started and stopped till the accumulated stresses had spent themselves. There was a similar rhythmic sequence in other parts of the fault, the frequency of the alternations depending on local conditions; and the total movement of dislocation at each point was accomplished by a series of steps and not by a single leap.

The time consumed in these reactions was not infinitesimal. The rate of propagation of changes in strain was of the same order of magnitude as that of earthquake waves in general, and the rate of propagation of the initiation of movement on the old fault plane may have been somewhat slower because of the necessity of accumulating a certain amount of stress increment to overcome the adhesion. It is probable that the completion of the fault required more than one minute, and it may have required more than two minutes. It is even possible that the displacement had been completed at the initial point before it began at the most remote.

In the succession of slippings and stoppings at any point of the fault plane each separate slip communicated a jar or pulse to the surrounding rock, and this pulse was propagated in all directions. The earthquake at any locality in the neighborhood of the fault consisted of such pulses from different directions. The general distribution of intensity indicates that the pulses weakened in transmission somewhat rapidly, whence it may be inferred that the particular pulses constituting the dominant elements of the local earthquake were those from the nearer parts of the fault.

If this conception of the earthquake is correct, the rhythm observed in the region of high intensity was a phenomenon distinct from the rhythm of harmonic waves. It was essentially a frictional rhythm, dependent on the relation of certain rock strains and rock stresses to the resistances afforded by adhesion and sliding friction. It was irregular not only because the intervals of local starting and stopping were unequal, but because it was derived from a considerable area of the fault surface, in which the local rhythms were neither harmonious nor synchronous.

The compounding of unevenly spaced pulses from different points of the fault plane caused both reinforcement and interference, introducing a character analogous to beats in music, but without the regularity of musical beats. It also at times made oscillatory motions swifter in one direction than the other, so that reciprocative accelerations were not always symmetrically arranged. In less technical language, the motion was jerky and included abrupt phases that were almost blows. The compounding also introduced variety in the direction of motion, especially at the end, when for a short time the

pulses from remoter parts of the zone of origin ceased to be overpowered by those from the nearest parts. The motion in that closing phase of the violent part of the earthquake has been compared by an observer to the motion of a vessel in a choppy sea; and I conceive that this comparison is the expression of a veritable analogy.

DISTRIBUTION OF INTENSITY.

When the isoseismal curves for this earthquake are drawn those for the higher intensities will show a remarkable elongation in the northwest-southeast direction. They will also show irregularties expressive of high intensity in the Santa Rosa Valley and other outlying areas. These features are related to the position and form of the zone or zones of origin. If drawn in detail they will show also the great influence of peculiarities of geologic formations. Detailed surveying has been attempted by the State commission only in San Francisco, partly because the results will there have the greatest practical value, and partly because the data are there most available. Notwithstanding the abundance of cracks, landslides, and broken trees in the region of high intensity, it is nevertheless true that natural structures in general are much less sensitive to earthquake violence than artificial structures, and for that reason grades of intensity are most easily mapped in cities.

The word "intensity" has various meanings as applied to earthquakes. As technically defined, it is the acceleration of the earth particle and is a quantity to be measured by the seismograph. But the field of instrumental observation is so limited that another definition practically obtains—that of power to destroy, a property which depends on the duration and direction of the motion as well as its acceleration, and which may have other factors.

It has long been known that buildings and other structures on ground of certain kinds are more susceptible to earthquake injury than on ground of other kinds, and these differences were strikingly illustrated in San Francisco. The general fact appears to be that the amplitude of vibration and the acceleration are greater in loose, unconsolidated formations than in solid rock. The firmer and more elastic a rock formation, the less the intensity of the earthquake shocks it transmits to buildings standing on it; and there is a gradation in this quality from the firmest bed rock to the loosest gravel, sand, and mud. For strong shocks, at least, the intensity is greater in loose formations saturated with water than in those that are dry.

Closely related to the control of intensity by the peculiarities of formations is the subject of surface undulations. Observers of strong earthquakes sometimes report visible progressive undulations of the ground, similar to water waves, and such observations are usually

made where the formations are alluvial. Doubtless many of the observations are fallacious, depending on a subjective illusion as to the direction of verticality, which arises from the horizontal movements of the observer's support; but some of them may also be objective. Not only is there a gradation in physical condition from dry earth through mud to water, but the shaking of a loose formation, whether wet or dry, overcomes the adhesion of particles and thereby imparts for the time being a mobility analogous to that of liquids. It is therefore conceivable that gravity waves, altogether analogous to those of water, may be produced by a violent earthquake on the surface of a loose formation. Certain ridges on soft ground caused by earthquakes in Japan are inferred by Omori and Kikuchi to represent such soil waves and to indicate a wave length (crest to crest) of 20 to 40 meters. The San Francisco earthquake produced a similar ridging on tidal mud in Tomales Bay, the average ridge interval being not more than half that of the Japanese examples. The Tomales Bay ridges are roughly parallel to the fault trace (which is close at hand), have about the same irregularity as wind waves, and originally ranged in height from 1 to 3 feet. They were observed chiefly, but not exclusively, on the body of mud already mentioned as having been shifted toward the southwest shore. The tract shown in Pl. VII lies so low as to be submerged much of the time, and the ridges had been so nearly obliterated when the views were taken that little remained besides an obscure indication of their ground plan; but an area nearer the head of the bay, and probably lying somewhat higher, not only seemed to have preserved its character when photographed (April 28; see Pl. VIII, A), but showed little change when visited nine months later.

Notwithstanding the persistence of the ridges at the last-mentioned locality, there is no reason to question the statement that the whole mud plain had the smooth surface common to tidal flats until it was disturbed by the earthquake. Nor do I find any room for doubt either that the ridges originated as waves on the surface of the mud while it was rendered quasi liquid by violent agitation, or that they persisted because the mud promptly resumed its normal coherence when the agitation ceased. It is by no means equally clear that the arrested waves were true gravity waves rolling across the mud plain. Whatever their mechanism and history, they illustrate a mode of response of wet, unconsolidated material to powerful earth tremors, they suggest an explanation of certain wavelike ridges produced on areas of made ground in San Francisco, and they contribute to an understanding of the peculiar destructiveness of the earthquake in such areas.

THE EFFECTS OF THE EARTHQUAKE AND FIRE ON VARIOUS STRUCTURES AND STRUCTURAL MATERIALS.

By Richard L. Humphrey.

GENERAL DISCUSSION OF THE EARTHQUAKE CONDITIONS.

On the 18th of April, 1906, the whole civilized world stood aghast at the appalling destruction which visited the city of San Francisco and vicinity. Three weeks later, for the purpose of studying the effect of the earthquake and fire on structural materials, the writer began the investigation herein described, lasting six weeks and covering the entire affected territory. It would be impossible, however, to describe the extent of the damage adequately or comprehensively in a report of this character. When we consider the terrific destruction wrought in the surface of the earth by the first movement or "slip," which developed structural weaknesses, it is not surprising that this movement and the resulting vibrations should prove so fatal to the structures of man.

In the fire that followed hundreds of thousands of people were rendered homeless and dependent on public bounty for shelter and the necessities of life. This phase of the disaster appealed to popular sympathy and drew spontaneously from all parts of the country contributions of food, clothing, household furnishings, and money for the relief of the destitute.

To the user of the materials of building construction the study of the behavior and relative efficiency of the various classes of such materials under the unusual and rigorous conditions imposed by the earthquake and fire is most interesting and instructive. The test was one of such violence that only structures of first-class design and materials and honest workmanship could survive. Flimsy and loosely built structures collapsed like houses of cards under the terrific wrenching and shaking, and many of the structures which withstood the earthquake were subjected to a second test in a fire which surpassed all the great conflagrations of recent years. Some of these structures

which successfully withstood the first test failed signally under the second, by reason of inadequate fireproofing. A very few withstood both tests successfully.

It is a generally accepted fact that no structure could have withstood the stresses produced by the movement of the earth at the "fault trace," along which the maximum intensity of disturbance was localized. The stresses produced by the vibrations at other points, however, could have been resisted with safety if proper design, first-class materials, and honest workmanship—constituting the whole secret of earthquake-resisting power—had been employed in the structures so located. In tall structures rigidity of construction, attained by adequate diagonal and portal bracing, is absolutely essential. In such buildings, owing to the inertia of the mass of the upper portion, the maximum bending moment exerted by the earthquake was applied at some point between the foundation and the top—generally just below the middle. While reenforced-concrete structures were few in the zone of seismic disturbances, these few stood the test by earthquake and fire in a highly satisfactory manner. Rigidity and stiffness and a high fire resistance are inherent qualities of concrete, and this material proved admirably suited to resist these extraordinary tests.

The destruction was greatest in structures built on filled ground, or on alluvial soils in the valleys of rivers, with foundations which did not go through to solid ground, the settling of the earth caused by the vibrations resulting in permanent displacement or distortion of such structures. At many places where great destruction took place, as at Palo Alto, San Jose, Salinas, Santa Rosa, etc., the structures were built on soft ground. In structures built on solid ground or rock formation the action was much less severe and was confined to shaking, producing a maximum oscillation in the upper portions of the structure.

In order to understand properly the conditions under which such destruction as that caused by the earthquake could occur, one should study the geologic conditions prevalent just prior to the earthquake.

The history of the Pacific coast is replete with records of seismic disturbances, the entire region being in a condition of unstable equilibrium and cut by long rifts in the surface, called "faults," which have produced a series of long, narrow valleys. The forces which produce elevations and subsidence of the surface also produce stresses, which finally overcome the adhesion of the opposing rift walls, and earthquakes take place in the slipping of these walls, through a few inches or a few feet, in the effort to adjust the stresses. These earthquakes are of two classes—volcanic and tectonic. The former occur in regions of volcanic activity, are shallow in extent,

and affect comparatively small areas; the latter not only extend to a much greater depth, but also affect much greater areas. The region north and south of San Francisco is regarded as particularly susceptible to earthquakes of the latter type.

A. C. Lawson has traced several of the "faults" referred to, and about ten years prior to the San Francisco earthquake he indicated the location of the present fault trace south of the Golden Gate. His relief map of California serves to show the lines of known faults by the parallelism of the ridges and valleys. In following these valleys one finds evidence of faulting on every hand—the scars and markings on the earth and rocks, and the presence of little lakes or ponds without visible source of supply other than the watershed of the adjacent ridges. According to Lawson, the coast of California is rising, and the seismic disturbances whose record is found in the rocks have been produced by movements in the process of upheaval and subsidence, of folding and faulting, which are, perhaps, greater along the coast of California than in any other part of the world. Whatever may be the causes of these movements, it is apparent that the resultant stresses relieve themselves by producing these faults or rifts in the earth's surface.

The average Californian becomes accustomed to the earthquakes which produce "temblors" of sufficient intensity to rattle windows. Prior to the great earthquake of April 18, 1906, these temblors were of frequent occurrence, but occasioned no alarm and, indeed, scarcely excited a passing interest. Over two hundred earthquakes were recorded during the period from 1850 to 1886, being more prevalent in the vicinity of San Francisco Bay than elsewhere. The writer is informed that during the period just prior to April 18 few if any noticeable temblors occurred. It is fair to assume, therefore, that the great earthquake resulted from an accumulation of stresses which would ordinarily have been relieved by smaller movements.

The relative intensities of earthquakes are indicated, on the Rossi-Forel scale, by Nos. I to X. All under V produce no visible destruction, and from V the destruction increases up to X, which represents those in which complete destruction takes place. The writer understands that the earthquake of April 18 is rated at IX on this scale.

This earthquake, the most severe in the history of the State, took place at 5 hours 13 minutes and 38 seconds a. m., Pacific time, the main shock lasting one minute and five seconds. Between this time and 7 a. m. about thirty minor shocks were recorded. A zone of destruction 50 miles wide was produced, extending for a distance of 150 to 200 miles north and south of San Francisco (see the map, fig. 1, p. 3), beginning at Point Arena, paralleling the coast to Fort Ross,

passing under the ocean bed just west of the Golden Gate, reappearing on the land at Mussel Rock, and following the Pilarcitos and San Andreas pipe lines of the Spring Valley Water Company in a direct line to Hollister. The zone included San Francisco Bay, Russian River, and the Sonora, Santa Clara, and Salinas valleys. The first movement was along this zone in a southeasterly direction, and the vibrations set up on all sides produced a continuous twisting, rocking, wrenching movement that brought down chimneys, walls, towers, etc. In the opinion of the California earthquake investigation commission the slip commenced at the northwest end of the zone, and the force which occasioned the rupturing or shearing movement was a progressively decreasing one to the southeast end. As in the earthquake of 1868, the destruction was greatest in proportion to the nearness to the fault trace, and in parts built on soft or alluvial soil, or on "made ground." The earthquake as recorded by the seismographs showed a horizontal movement of about 3 inches and a vertical movement of about 1 inch, the velocity of propagation being about 2.1 miles per second. The wave movement was long and slow in hard soil and rock and comparatively short and incoherent in soft ground.

EFFECTS ON STRUCTURES OUTSIDE OF SAN FRANCISCO.

In considering in detail the damage wrought by the earthquake one must look for evidence in the country surrounding San Francisco, since the fire in that city obliterated most of the signs of the damage.

The greatest loss in the city of San Francisco was principally the result of the fire, which was rendered uncontrollable owing to the wrecking of the water-supply system by the earthquake. (See the maps of the city and vicinity, Pls. LVI and LVII.) An examination of the damage to the system at once suggests itself, especially as some of the main conduits are located on or near the fault line.

The city is supplied principally by gravity from three main distributing reservoirs, viz, University Mound, College Hill, and Lake Honda; there are also two supplementary sources—Alameda Creek, on the east side of the bay, and Lake Merced. The University Mound reservoir, having a capacity of 33,000,000 gallons, is supplied from Crystal Springs Lake through 17 miles of 44-inch wrought-iron pipe, carried for a considerable distance on trestles over the marshes. The College Hill reservoir has a capacity of 15,000,000 gallons and is supplied from San Andreas Lake through 14 miles of 44-inch, 37-inch, and 30-inch wrought-iron pipe. The Lake Honda reservoir, with a capacity of 31,000,000 gallons, is fed from Pilarcitos Lake through 16 miles of conduit, 1½ miles of which is wooden flume and the remainder cast-iron and wrought-iron pipe and brick tunnel. Of the two supplementary supplies, the water from Alameda Creek is car-

ried 27 miles, crossing San Francisco Bay through submarine pipes, and thence passing through the Crystal Springs conduit to the city; that from Lake Merced is pumped into the Pilarcitos conduit and thence to the city.

In company with Herman Schussler, chief engineer of the Spring Valley Water Company, the writer made a detailed examination of the principal conduits and reservoirs. On the San Bruno marsh the 44-inch line to the University Mound reservoir had been thrown off the trestle for a distance of 1,300 feet; and, while the pipe was readily repaired, the trestle had to be rebuilt, as many of the timbers had rotted. Near Baden the line had been telescoped 42 inches, shearing off an 8-inch gate valve. The reservoir itself was undamaged, yet its three days' supply was rendered useless by the breaks in the cast-iron distributing mains.

The only damage done to the conduit between San Andreas Lake and the College Hill reservoir was at Baden, where the slip joint had been broken, tearing out the four cast-iron lugs—an effect indicating a force of at least 2,000,000 pounds.

The principal breaks in the Pilarcitos conduit, which was so badly damaged that the company decided to abandon it, were examined. This conduit had been located for convenience in one of the long, narrow valleys, and therefore on the line of an old fault. It is evident that it would be futile to attempt to build this conduit strong enough to withstand a slip on the fault line. The breaks in this 30-inch wrought-iron pipe ranged from 30 inches to 6 feet in length. At other points it was telescoped and twisted beyond repair. (See Pl. IX.) The Pilarcitos conduit crosses Frawleys Gulch on a trestle. The movement of the earth produced a compression in the pipe line at this point, which threw it off and wrecked the trestle, and the water in the conduit leading to the trestle line was released so rapidly that it formed a vacuum, which caused this conduit to collapse, as shown in Pl. X, A. The conduit crosses and recrosses the fault for a distance of 6 miles south of Frawleys Gulch. The 30-inch wrought-iron pipe line was torn and twisted at each crossing, while the earth dam of Pilarcitos Lake was uninjured.

The San Andreas earth dam lies across the fault, the crossing being about 100 feet from its east end, and the dam shows a disturbance for a distance of more than 100 feet. One of the worst cracks runs diagonally across a culvert 4 feet 6 inches in diameter, which appears to be uninjured. Although San Andreas Lake had considerable water in it, no appreciable loss of head was observed. There is a roadway over the dam, along which runs a fence. Both were offset at the fault line about 3½ feet. A wooden flume used for diverting storage water to the reservoir lines crosses the fault, and was wrecked at that

point for 50 feet. A brick conduit used for waste purposes extends across the fault. All the four rings, of hard-burned brick, are laid in first-class Portland-cement mortar, making a first-class piece of work in every way. This conduit, which is 9 feet 6 inches in diameter, was crushed together at the crossing.

The Searsville dam, a structure similar to the San Andreas earth dam, 1 mile east of the fault line and parallel to it, was also found to be uninjured.

Very little damage was done to the pumping stations, and the steel standpipes of this company were not injured. The Lake Honda reservoir was slightly damaged by a crack in its concrete lining. No damage was done to the Alameda Creek supply, except to the connection at the Belmont pumping station.

The concrete dam near San Mateo, at the lower end of Crystal Springs Lake, parallel to the fault line and a few hundred feet east of it, was undamaged. This dam, a view of which is given in Pl. XI, *B*, is built of large blocks of concrete, thoroughly keyed together and molded in place, each block containing between 200 and 300 cubic feet. The dam is 680 feet long, with a present height of 146 feet. When completed it will be 170 feet high, 176 feet thick at the base, and 25 feet thick at the top. It is arched upstream to a radius of 637 feet.

The clay-core earth dam of the upper Crystal Springs Lake lies across the fault line at nearly right angles. This dam is now maintained as a county causeway, equalizing pipes having been placed through it. At the time of the earthquake the water was at the same height on each side, and the absence of any "head" made it impossible to tell the extent of the damage. The dam moved about 6 feet, however, this fact being shown clearly by an offset of that amount in the fence which runs across it. The roadway over the dam also shows the same offset, although not so clearly.

The water supply of San Francisco, as compared with that of other cities, was fairly good and had a rated capacity of 36,000,000 gallons per day. The failure to control the fire by reason of the crippling of the water supply was not due to the failure of the system outside of the city, but to the breaks in the distributing mains within the city, which rendered unavailable about 80,000,000 gallons of water stored within the city limits. These breaks occurred (see the map, Pl. LVI) wherever the pipes passed through soft or made ground. No breaks occurred where the cast-iron pipe was laid in solid ground or rock. It is evident that in earthquake countries water-supply pipes, at least, should be so laid as to avoid the action of slips, settling, and ground movements of all kinds. The pipe lines should also be arranged with gates and by-passes, making it possible to cut

out any portion of the system which may become crippled. There should also be some means of preventing the loss of water which is occasioned by breaks in the house service pipes.

While one of the main conduits was badly damaged wherever it crossed the fault, this damage was no greater than that done to any other structure that was situated at the fault line. Structures so located were torn apart, the gap in the case of a fence (Pl. I, *B*) or road (Pl. I, *A*) being from 6 to 20 feet, according to local conditions. In the country around Fort Ross there were many trees located on the fault that showed the effect of the slip. Great redwood and pine trees were either twisted out of normal position or split (Pl. II) from the roots up for distances of 35 feet or more, even when perfectly sound. This splitting action was due to the earth on the west of the line of faulting moving the roots on that side, a motion which tended to pull the tree apart. Where the tree had some defect or was unsound (as from dry rot) the action was even more marked and the destruction much greater. Redwood trees grow to great heights and are perfectly straight, and to find one out of plumb is very unusual.

Another interesting example of the effect of the slip along the line of the fault is afforded by the Southern Pacific Railroad bridge over Pajaro River near Chittenden station. This bridge crosses the fault obliquely at a very acute angle—about 10°. It consists of two girder shore spans of 50 feet each and three Pratt truss river spans of about 100 feet each. The piers and abutments are built of concrete, with granite coping and bridge seats (Pl. XI, *A*). The bridge was badly racked by the movement of the earth, which dragged the piers and abutments. The movement of the south abutment was about 24 inches, a distance sufficient to leave the girder without support. The ground also moved a greater distance than the abutment—perhaps 8 or 10 inches farther. The movement of the earth tending to pull the piers from under the trusses was resisted by the anchor bolts, resulting in a cracking of the piers, apparently on the lines marking the different daily batches of concrete used in constructing them. The granite caps were moved out of position and many of them cracked, and the anchor bolts were twisted and bent. The bridge was put into service by the construction of a timber support.

In the vicinity of Los Gatos, where the line of faulting passes through the Santa Cruz Mountains, it crosses the first tunnel of the narrow-gage railroad to Santa Cruz near Wrights. In this tunnel a portion of the loose roof, of shale on a layer of serpentine or soapstone, caved in, completely closing the tunnel. A house on this fault line near Wrights was split in twain, the movement of the earth throwing the west side of the house from its foundation (Pl. X, *B*).

The Saratoga reservoir of the San Jose Water Company lies in a saddle of the Santa Cruz Mountains between Saratoga and Los Gatos, and the fault line crosses it at right angles, the cracks extending through the body of the dam. The reservoir was full at the time, but there was no apparent loss of head.

As already stated, in the country bordering the line of faulting the damage done was greater in soft or alluvial soil or made ground. Most wooden water tanks on low supports were wrecked, not only in the vicinity of the fault line but throughout the affected zone, the failure being due to a lack of lateral bracing of the trestle support. Chimneys generally collapsed, the cause being the unequal movement of the inelastic brickwork and the usually elastic frame structure surrounding it. Wooden buildings on good foundations stood well, the chief damage being to the chimneys and plastering. The alluvial or soft soil forming the banks of rivers generally moved toward the river under the earthquake vibrations, the settling of the ground being most marked (Pl. VIII, *B*). The country in the vicinity of Salinas River presented interesting features of this character. The county road crosses the river near Salinas on a wooden bridge, and the slipping of the banks carried the south abutment 6 feet toward the river. The ground was badly cracked and there were a number of slips in the neighborhood. The road leading to Spreckels's sugar mill, 4 miles south of Salinas, was also greatly damaged by the slips. Spreckels's sugar mill (Pl. XII, *A*) is located on soft alluvium. The main building, which is 500 feet long, is said to be the largest sugar mill in the world. The vibrations of the earth jarred the brickwork loose at the end of the building, which buckled in the middle, where there were no floors above the second floor. The damage to other buildings was also extensive. The town of Salinas itself was severely shaken. The high-school building and some of the buildings on the main street were damaged, chimneys were thrown down, and a water tank of the Southern Pacific Railroad, supported on a steel trestle near the station, collapsed.

Along the Bay of Monterey the whole shore slipped about 12 feet into the bay, the movement buckling the rails on a railroad trestle and the cars dropping about 5 feet. A frame house and surroundings moved 12 feet, still maintaining their relative positions. In Monterey the principal damage was in the loss of chimneys and cracking of plaster.

At San Jose, located on the soft alluvium of the Santa Clara Valley, the destruction was extensive. The post-office, a very substantial building, lost its tower, which was laid up in lime mortar, and was deficient in lateral bracing. The walls were of brick with a 4-inch or 6-inch stone veneer, and there was a wooden-framed slate-covered apex. The collapse of the tower damaged the pavement, and

to some extent the building itself. The damage to the hall of records, along the end walls, was due entirely to defective construction. The Hall of Justice (Pl. XII, *B*), which was completed in 1905, had the wall along the cornice line thrown down. The reenforced-concrete roof contributed no little to the support of the walls of the building, and had the stonework been less heavy and of better quality the damage probably would not have been so extensive. The high school (Pl. XIII, *B*), a flimsy structure of brick with wooden frame, was so badly wrecked that it had to be torn down as a matter of safety. The destruction of the buildings along First street, the principal business thoroughfare, was also extensive. Lime mortar, flimsy framing, poor design, and lack of tie between floor and roof members and walls were the causes of these failures.

Perhaps the worst example of poor design, bad workmanship, and poor materials in the earthquake territory, except in the city of San Francisco, is the insane asylum at Agnew, about 6 miles northwest of San Jose, consisting of a main building surrounded by a number of others—all flimsily constructed brick structures with timber frames. The construction of these buildings, with their thin walls (in many places devoid of mortar) and light, insufficient wooden framing, indicates a criminal negligence that is appalling. One hundred and seventeen patients and attendants lost their lives, principally from the fall of the central tower of the main building. The brick stack of the power plant and the towers of surrounding buildings collapsed. In the farmyard near by is a water tank supported on a wooden trestle. This tank moved about 10 inches, while less than a stone's throw away are four water tanks supported by a diagonally braced steel trestle, which were undamaged (Pl. XIII, *A*).

The most interesting ruins are those of the Leland Stanford Junior University, at Palo Alto, 6 miles east of the fault line. These buildings were on a soft soil and were therefore subjected to the severest earthquake conditions; and as they represent several different types of construction they afford a profitable study in the earthquake-resisting power of various structures and structural materials. The destruction was very great, most of the buildings being wholly or partially destroyed.

Three types of wall construction were represented—(1) solid stone, (2) brick and stone veneer, and (3) reenforced concrete. The buildings of the first-mentioned type, which were erected by Senator Stanford by day labor, were examples of good substantial work, and the damage to them was not so great. The stone-veneer buildings represent a later type, resorted to as a matter of cheapness, and suffered the most. The third type, of reenforced concrete, sustained practically no damage. The stone-veneer buildings have a 4-inch or

6-inch face of stone, poorly bedded, containing a large percentage of spalls, the lime mortar being of good quality. The construction is fairly common in other parts of the country. The roof trusses were not anchored to the walls, but to a great extent were butted against the walls; the floor joists rested in the walls and were not tied. Under the vibrations the walls were pushed out of plumb and, having no proper connection with the floor and roof members, collapsed.

The gymnasium and library presented interesting features. The dome of the library was supported by a skeleton of steel, and although the surrounding walls collapsed, this dome was not damaged (Pl. XV, *A*). The gymnasium dome rested on intermediate brick walls, which collapsed with the dome (Pl. XV, *B*).

The boys' dormitory (Encina Hall) was built of stone, and was one of the buildings erected by Senator Stanford. The chimneys of this structure collapsed and crashed through the roof and floors, killing one student and injuring several others. The walls themselves were but slightly cracked. The girls' dormitory (Roble Hall) had walls of reenforced concrete with wooden floors. The chimneys on this structure also collapsed, but no other damage was done, the walls being left intact, without any cracks.

The memorial arch (Pl. XVI) was a poorly designed structure, 100 feet high, with stone-veneered walls. The structure above the arch ring was hollow, and an attempt had been made to stiffen it by the use of a number of I beams. These beams were not tied to the stonework, but simply rested upon it, and under the action of the earthquake they became battering rams and helped to accomplish the destruction of the arch. The arch as first designed was 75 feet high, and it will be noted that the earthquake reduced it to the height originally intended (Pl. XVI, *B*).

The memorial chapel, one of the most beautiful buildings in this country, was almost completely wrecked (Pl. XVII, *B*) by the collapse of the tower. A platform of steel beams had been placed under the clock as a precaution against the chance falling of the pendulum, and this platform saved the clock. The damage done to the mosaic work and the interior decoration is probably irreparable.

The chemical laboratory was damaged by falling chimneys, and gable walls were pushed out and suffered considerable damage by the collapse of the assay stack. The plastering was also badly cracked. Great damage was also wrought in the power plant of the mechanical engineering department by the falling of the stack.

The quadrangle, or main academic portion of the university, was built by day labor and was a fair piece of work. The cloister (Pl. XVIII, *B*) suffered considerably, the bases and caps of the columns being spalled and chipped, indicating that they must have been subjected to a rocking motion. The arches apparently opened up, for in

a number of them the arch stones had dropped partly out of place. The department of geology (Pl. XVIII, *A*), the newly completed end of the quadrangle, suffered the greatest damage; many of the walls will have to be rebuilt, having been either cracked very badly or destroyed entirely. The plastering was badly cracked and showed the outline of each sheet of metal lath. Where reenforced concrete was used the ceilings were free from cracks.

The most interesting building is the museum (Pl. XIV, *A*), which consists of a central pavilion of reenforced concrete and wings of brick plastered with cement mortar. The columns of the central pavilion are solid concrete, having been cast in place. This building had wooden floors. The wings were wrecked by the earthquake, but the central pavilion escaped injury, although its contents were more or less damaged, principally by being shaken from their positions.

Although the destruction at Stanford University was very great, the character of construction was fair and did not suffer by comparison with that used in other parts of the country. The excellent qualities of reenforced concrete and its ability to withstand earthquake shock were strongly demonstrated.

The town of Palo Alto suffered considerably from the earthquake. Chimneys were generally thrown down. A number of buildings were wholly or partly wrecked, the causes of the failures being similar to those in other sections, consisting largely of defects in design, lack of adequate bracing, poor mortar, and bad workmanship. Three concrete-block buildings were either wholly or partly destroyed and have especial interest, since they have been cited as evidence of the failure of concrete blocks. Two of these buildings are located on Alma street opposite the station and on opposite sides of University avenue—the Thiele Building (Pl. XVII, *A*), a partially completed three-story structure, which was entirely wrecked, and the Fuller Building, a two-story structure, which also collapsed. The concrete-block walls, 13 inches thick, laid in cement mortar, were not braced in any way—the joists, 1½ by 13, simply resting upon the wall. When the building vibrated, the wall was pushed out and collapsed because there was nothing to restore it to its normal position. This defect was more clearly shown in the one-story building of Vandervoort Brothers (Pl. XIX, *B*), in which the roof truss was simply butted against the block wall without tie or other connection.

At Santa Rosa the destruction was greater than in any other section affected by the earthquake, and the fire that followed completely wiped out the business section of the town, which suffered a greater proportionate total loss than San Francisco. A concrete-block building (Pl. XIX, *A*) in this town escaped with slight damage at the cornice only, where the blocks were thrown down, the reason being that the walls were tied to the roof timbers by tie-rods which

held the walls and roof together and made them move as a unit. The cornice was rebuilt before the view was taken. While buildings of brick and stone collapsed all around this one, it received practically no damage and demonstrated that structures that will successfully withstand earthquake shock can be built of concrete blocks. The other buildings at Santa Rosa did not present any interesting features, as they were mostly defective in design and workmanship and the material was generally poor. The city hall, the court-house (Pl. XIV, *B*), the Masonic Temple, the Keegan-Brush Building, and the St. Rose Hotel were all completely wrecked, and added their testimony against poor mortar in brickwork, light wooden frames, and insufficient bracing.

Towns like Berkeley and Oakland did not suffer as greatly from the earthquake as many neighboring towns, the reason lying in the fact that these towns are built on solid ground or on rock. In Berkeley, while chimneys were shaken down, there was no extensive earthquake damage. The Greek Theater, a massive structure of concrete, was uninjured. In Oakland, however, greater destruction occurred. Just outside of Oakland is located the Mills College for Girls. The science building had brick walls plastered with cement mortar, and was considerably damaged by the shaking it received and the falling chimneys. The building had wooden floors and was considerably racked, the walls being pushed out slightly. Within a few feet is the bell tower (Pl. XX, *B*), a reenforced-concrete structure 80 feet high with walls 4 inches thick, which was not damaged in the slightest degree.

CONDITIONS IN SAN FRANCISCO.

GENERAL EARTHQUAKE CONDITIONS AND EFFECTS.

Within the city of San Francisco (see the map, Pl. LVI) the havoc wrought by the earthquake depended on the character of the construction and its foundation. Bordering San Francisco Bay, from Telegraph Hill to Mission Creek, the land consists of mud flats, which have been gradually filled in, and on this land many large commercial buildings had been erected, among others being the Union Ferry building, the post-office, the mint, and the custom-house. Adjoining this filled land was comparatively level ground composed of sand and clay formed by the wearing away of the hillsides and by the incoming sand from the seacoast—a fringe of soil on which were located many of the principal buildings. From Telegraph Hill southwestward along Russian Hill to Sutro Heights runs a ridge of rocky hills composed of indurated clay shale, with serpentine and other rocky formations on their highest summits.

The signs of destruction wrought by the earthquake in the city of San Francisco were more or less obscured or in many places entirely obliterated by the fire. The best evidence of the earthquake can therefore be obtained outside the burned district, and the following notes cover the most important examples of damage due to the earthquake alone.

As in districts outside of San Francisco, the greatest damage was done to those structures having insufficient foundations built on soft alluvium or filled ground. The settling of the ground in the mud flats along San Francisco Bay and of the filled ground in old water courses was accompanied with great destruction. It was in such ground that the greatest number of breaks occurred in the cast-iron gas and water mains and the sewers. The breaks in the sewers were not so evident as those in the gas and water mains, for the reason that the latter were under pressure and breaks in them resulted in breaks in the streets themselves. The most noticeable destruction resulting from the settling of soft or filled ground occurred in Howard and Shotwell streets between Seventeenth and Eighteenth streets, Bryant street betwen Ninth and Tenth streets, Dore street between Bryant and Brannan streets (Pl. VI, *A*), and at the corner of Seventh and Mission streets. The settling was greatest in Howard, Dore, and Bryant streets, being in Dore street at least 5 feet.

On solid ground the earthquake had a rocking effect which produced X cracks (Pl. XXII, *A*) in the brick or stone walls of those buildings which were deficient in diagonal bracing. This was especially true in the upper stories of tall buildings, the cracks generally appearing in the piers between windows or around doorways. The brick curtain walls of buildings well braced diagonally, brick walls reenforced with band iron, and well-buttressed brick walls, as in such old structures as the Palace Hotel, Sailors' Home, St. Mary's Hospital, Synagogue Emanuel (Pl. XXI, *B*), and others, and walls of reenforced concrete proved best adapted to withstand this rocking action. The Palace Hotel was stiffened with cross walls in addition to the band-iron reenforcement in the brickwork, and is in good condition as far as earthquake effects are concerned. It was completely gutted by fire, however (Pls. XXX, *B*; LII, *B*), being a nonfireproof structure with wooden floors and roof which yielded readily.

Weak and flimsy framing, insufficient bracing, and poor mortar were the cause of most of the failures in San Francisco. The Albert Pike Memorial, a recently completed building on Geary street west of Fillmore, was seriously damaged, and so also was the adjoining Jewish synagogue (Pl. XXI, *A*), which had not been quite completed. Both buildings are examples of defective design and workmanship. In the girls' high school the damage to the brick walls resulted from a lack of proper tie between the floor and roof timbers and the walls

and the poor quality of the mortar used in the brickwork. Again, in the Hahnemann Medical College, on California street near Maple street, the destruction of the end walls was the result of bad design, the roof trusses butting against the walls and the floor timbers resting upon the walls without adequate tie. The poor quality of the mortar permitted a ready disintegration of the brick-veneered walls, although some band iron had been used for the purpose of strengthening them. The Cathedral of St. Dominic, with its high, unbraced brick walls and its peculiar wood-sheathed spires, also proved a victim of poor design and workmanship; the sheathing on the spires was shaken off and the collapse of the walls resulted in extensive damage to the interior.

In interesting contradistinction to these failures was the Sailors' Home, erected in 1858 for use as a marine hospital and condemned as unsafe after the earthquake of 1868. Its heavy brick walls, reenforced with band iron and further stiffened by cross walls thoroughly bonded, are in excellent condition. The building rests upon rock and the framing is excellent; the rafters are fastened to a wall plate which ties the walls, causing the structure to move as a unit. The only cracks occurred where partition walls which had been added were shaken loose from the main walls and around the archways leading to the main stairway on the second and third floors, where no extra stiffening of the walls had been provided. The building in all other respects suffered no damage, there being no new cracks apparent in the exterior walls.

The old red-tiled Spanish Mission Dolores (Pl. XXIII, *B*), built in 1777, with its adobe walls and wooden frame, was not injured, while its more modern successor was greatly damaged. The complete collapse of the tower of the new Mission Dolores was not brought about directly by the earthquake, but the damage was such that the tower had to be taken down, as shown in Pl. XXIII, *B*.

The group of buildings comprising the plant of the San Francisco Gas and Electric Light Company, built on the soft ground along San Francisco Bay just west of Fort Mason, was badly shaken, and none of the buildings escaped damage. The collapse of the stack wrecked the light slate-covered iron roof of the power house and started the fire that destroyed the roof of the boiler house. The ground settled very considerably under the vibrations of the earthquake, and further destruction was caused by the unequal settling of the building. The main shock appeared to come from the north, and the north walls received the greatest damage. The end wall of the retort house was pushed out 1 foot at the center, but was saved from collapse by the tie-rods which held it to the roof truss. The walls were cracked at the northwest and northeast corners. The scrubber and gas-tar holder houses were wrecked, the heavy wooden

roof trusses collapsing. Nearly every wall was moved slightly, but the brickwork was generally very good, and apparently had cement in it. The exhaust house had three intermediate walls, 18 inches thick at the top. The north wall and the next one fell into the building, the side walls being pushed out 6 inches. The building had wooden roof trusses and the north truss cracked at the center mortise. The floor settled badly around the condensers. The gas holder collapsed from the sudden release of the gas due to a break in the mains. The trestle pier extending into the bay also collapsed.

Most of the structures built on piles along the bay suffered considerable damage, especially the frame sheds on the wharves. The Union Ferry Building (Pl. XLVI, *A*), the terminus for all the ferries plying on the bay, is built on piles. It was more seriously damaged by the earthquake than would appear at first sight, and barely escaped the fire also. It is of interest to consider in some detail the behavior of this structure under the action of the earthquake. The ten-story tower was so seriously damaged as to require the removal of the masonry walls, and will probably have to be rebuilt. This tower consists of a steel frame which was inclosed with heavy sandstone walls backed with brick for several of the lower stories, and with sheet metal above. The floors above the masonry part were of stone concrete reenforced with expanded metal between **I** beams. The brick walls were badly shattered, and a large section was thrown out just below the clock on the west front, while on the east front a large mass fell through the skylight onto the upper story of the main building. There were but few cracks in the north and south walls. The steel time-ball staff was badly bent, indicating a considerable movement of the top of the tower, probably resulting from the first shock. The steel work was severely racked, the greatest damage being just below the middle. Some of the diagonal braces were sagged, having been stretched beyond their elastic limit (Pl. XLVI, *B*). In the southeast corner of the third story the bottom and top loops of one of the 2-inch square diagonals were pulled apart, and several of the rivets in the angle connection were sheared off; in the southwest corner also the top diagonal loop pulled apart, the diagonal being considerably bent; in the northwest corner seven of the eight ¾-inch rivets in the angle of the connection for the diagonals were sheared off (Pl. XLVII, *B*); and in the northeast corner all but 2 inches of the top angle was sheared, and the north diagonal was bent, the loop having been pulled apart. On the second floor, in the northeast corner, the top east diagonal connection pulled away, shearing the rivets; in the southeast corner the top angle of the diagonal connection sheared for about 2 inches, and four of the 1-inch rivets holding the cover plate of the southwest column (Pl. XLVII, *A*) were sheared, as were also

two of the rivets holding the clip support for the west girder. The floor of the main building consisted of groined arches of stone concrete springing from concrete piers supported by cluster piles. The self-supporting walls of sandstone backed with brick were more or less shaken, and the piers of the driveways were badly cracked; the floors were of stone concrete reenforced with expanded metal between I beams and supported by cast-iron columns. The concrete in this building appeared to be undamaged.

Most of the entrances to the cemeteries were wholly or partially wrecked, and the burial vaults and gravestones were all more or less disarranged. It has been estimated that perhaps 60 per cent of the monuments, vaults, etc., in cemeteries were overturned or moved.

In Golden Gate Park nearly every stone or brick structure was damaged. The emergency hospital, a single-story brick and stone-veneered building, lost its gable walls and was damaged in the same manner as other structures having improperly bonded walls laid in lime mortar, and deficient in proper ties between the masonry and the other structural parts. The gable walls of the restaurant in the children's playground were thrown down by the earthquake, but the greatest damage resulted in the settling of the foundation of one of the columns, which caused the collapse of the structure. The music stand, a stone-veneer brick-backed structure, was racked and shaken. Part of the pediment was shaken loose, and many of the columns were spalled and moved. Some of the walls of the museum were thrown down, and its contents were more or less damaged. All the monuments were damaged. The Francis Scott Key monument (Pl. XX, *A*) was racked so badly that the arch stones were shaken loose, the columns spalled at cap and base, and the monument as a whole moved on its foundations.

The most interesting structure in Golden Gate Park is the cyclorama (Pl. XXIII, *A*), on the top of Strawberry Hill, built about fifteen years ago. The top of the hill had been leveled off in order to form a foundation. The cyclorama consisted of circular walls of reenforced concrete, the aggregate of which was a hard shale crushed to concrete size. This material was very inferior and yielded a poor concrete. The reddish-brown effect was obtained by means of a veneer ($1\frac{1}{2}$ to 4 inches thick) of a concrete consisting of crushed brick, sand, and cement. The reenforcement in the base consisted of four $\frac{7}{8}$-inch cables of thirty strands each. The reenforcement of the columns consisted of $\frac{3}{4}$-inch twisted bars and $\frac{1}{2}$-inch stirrups. The entrance, with its very heavy, massive top, should have been of hollow-construction reenforced concrete. The settling of the foundation or fill under the vibration of the earthquake caused the structure to collapse. The slip (Pl. XXII, *B*) occurred principally on the northeast side, the movement being 4 or 5 feet. The principal crack in

the base was about 11 inches wide, with a half-inch horizontal crack leading from it along the reenforcement. The floor is in good condition, except the pavement, which broke into blocks, most of the planes of fracture coinciding with the actual joints between the different sections. Under the circumstances—the undermining of the foundation by the slip as described—the structure developed remarkable strength. No brick or stone structure could have stood the shock so well. The rustic railing around the outside of the walk (Pl. XXII, *B*), which was of wrought-iron pipe covered with wire mesh and plastered with Portland-cement mortar, was distorted by the slip, but otherwise uninjured.

At the bottom of Strawberry Hill is a bridge crossing over Stow Lake. This bridge is made of concrete, and showed no signs of cracking, although the banks of the lake slipped into the water.

BEHAVIOR OF INDIVIDUAL STRUCTURES.

GENERAL STATEMENT.

The numerous fires that broke out all over the city were doubtless caused by the collapse of chimneys and the breaking of electric connections. These fires were at first confined to the territory south of Market street, and it is said that by 8 a. m. on the morning of April 18 more than fifty fires were recorded. The early failure of the water mains rendered the city helpless and placed it at the mercy of the flames, the fury of which for three days threatened to complete one of the greatest disasters of recent years and to obliterate one of the most beautiful cities in the country. The conflagration was finally checked, at the barrier presented by a wide avenue, by a change in the direction of the wind and through the efforts of the fire department, using water pumped from the bay at the foot of Van Ness avenue.

San Francisco consisted principally of frame and brick structures, with perhaps forty or more so-called "fireproofs," a few buildings of slow-burning construction, and the substantial Government buildings. Many of the buildings contained mercantile stocks, and most of them were exposed to exterior fire conditions of maximum severity. Since every type of construction was represented, the ruins afford a most excellent opportunity for comparative study, although the scope of the information obtained is incomplete, as a water test is lacking.

In comparing the behavior of the various structures and structural materials it has been thought best to describe the condition in which certain individual buildings were left by the earthquake and fire, and to present the salient features of these buildings by illustrations with descriptive legends. The following descriptions, which for

convenience are arranged in alphabetical order, cover the structures not previously mentioned that were inspected by the writer, the total number embracing nearly every building that was left standing in the burned district. The locations of these buildings can be found by reference to the map, Pl. LVI, and to the panorama, Pl. LV.

ACADEMY OF SCIENCES BUILDING.

The Academy of Sciences building, 819 Market street, views of parts of which are shown in Pls. XXIV, *A*, and XXV, *B*, was of ordinary concrete construction and six stories high, and was completely destroyed.

A six-story annex having brick walls, concrete-filled cast-iron columns, and reenforced-concrete floors, was connected to the main building on the rear. The brick walls of the annex were badly cracked by the earthquake, and the building was subsequently completely gutted by fire. The structure itself passed through a fairly hot fire successfully, although surrounded by buildings which were completely wrecked. Plaster of Paris was used on the concrete-filled cast-iron columns and seemed to stand fire much better than lime mortar. These columns are shown in Pl. XXV, *B*, a view taken from the third floor looking southeast. An interesting feature of the building was the concrete-filled cast-iron column that supported the south wall. Owing to the unequal expansion of the cast iron and the concrete the cast iron failed, bulging from the heat and cracking on cooling, as shown in Pl. XXIV, *A*. The $\frac{3}{4}$-inch or 1-inch thickness of concrete which covered the reenforcing bars proved insufficient in the basement, where the fire was fairly hot. The heat expanded the bars, thereby ripping off the concrete layer and leaving the rods exposed.

ÆTNA (YOUNG, OR COMMISSARY) BUILDING.

The five-story Ætna Building (Pls. XXIV, *B*; XXV, *A*; XXIX, *B*), on the southwest corner of Spear and Market streets, was occupied by the Sellers Brothers Hardware Company. It was built on piles and had self-supporting walls of gray granite, pressed brick, and terra cotta. The steel columns and girders were fireproofed with expanded metal, plastered. The expanded-metal reenforced-concrete floors rested upon steel girders with intermediate ribs of concrete supported by 5-inch by $\frac{1}{2}$-inch bands of steel without fireproofing which hooked onto the top flanges of the girders.

One panel of the fifth floor, which was rather heavily loaded with tin plate, collapsed because of the expansion of the above-mentioned steel bands from the heat, which was sufficient to volatilize the tin even from the middle sheets of the pile. The fall of the load of tin

plate caused the failure of the third floor, as shown in Pl. XXIX, *B*. The plaster protection of the columns was in fair condition, and the columns were uninjured. The principal damage from earthquake was to the brick walls, the south and west walls showing a number of cracks. The granite trimmings around the doorway and the terra-cotta trimmings of the building were badly spalled by the fire, as shown in Pl. XXIV, *B*. The basement floor, which was of concrete 7 or 8 inches thick, was pushed up under the sidewalk, reducing the headroom at this point from 8 feet to 3½ feet, approximately. This bulging was probably caused by settling (Pl. XXV, *A*), as the foundation piling did not extend under the sidewalk.

APPRAISERS' WAREHOUSE (UNITED STATES CUSTOM-HOUSE).

The four-story custom-house building, on Jackson, Washington, and Battery streets, shown in Pl. XXVIII, *A*, passed through both earthquake and fire without injury, although located on the alluvial flats. All the buildings around it were burned, but the fire did not gain a foothold in this building, and there was, therefore, no fire test. As an example of successful resistance of the earthquake test, however, this building stands as a favorable testimony to first-class materials and workmanship. The walls were of brick, with granite ornamentation, and the roof was slate covered. The partitions and cross walls were all of solid brickwork, and the only damage that they sustained consisted of a few cracks in the archways near the stairways on the upper floors.

ARONSON BUILDING.

The ten-story Aronson Building, on the corner of Third and Mission streets, had a steel skeleton with hollow-tile partitions and fireproofing for the columns. The floors were of concrete reenforced with expanded metal.

Two of the columns on the first floor buckled by reason of the failure of the hollow tile (Pl. XXVII, *B*), the columns being shortened about 10 inches. Columns also buckled in the basement and on the fifth, eighth, and tenth floors. In the basement two columns were fireproofed with concrete, and remain in first-class shape, but near them are two badly buckled columns which were fireproofed with terra cotta. This result is an excellent object lesson on the merits of the two systems of fireproofing. The sandstone was badly spalled by fire, and the walls were badly racked by the earthquake. The cast-iron stairways were very much damaged. The fire in this building was not severe.

BEKINS VAN AND STORAGE COMPANY'S BUILDING.

The building in process of construction by the Bekins Van and Storage Company, at the corner of Thirteenth and Mission streets, was the only example of the pure type of reenforced concrete in the city (Pl. XXVII, *A*). Two of the six floors were erected, the walls being made of brick laid in lime mortar and the floors and columns of reenforced concrete.

The walls were badly cracked by the earthquake, but the reenforced concrete was not injured. Considerable furniture stored in the building was burned, and the heat slightly blistered the under surface of the concrete floor, which was still green at the time of the disaster.

BULLOCK & JONES BUILDING.

The Bullock & Jones Building, on Sutter street west of Montgomery street, is an eight-story steel skeleton with floors of reenforced cinder concrete, hollow-tile partitions and column protection, and bearing walls of ornamental terra cotta and terra-cotta pressed brick. The reenforced-concrete floor arches were haunched between steel girders, but were not continuous over the girders.

The earthquake damaged the outside very considerably. The building is of rather flimsy construction, and it is a wonder that the fire did not wreck it. The terra cotta was badly spalled by the fire, especially around the windows, and the hollow tile failed badly, both in partitions and as column protection. The 3-inch terra-cotta partitions failed generally, and several columns buckled on the third and eighth floors (Pl. XXVI, *A*). The elevator inclosure, which was plastered on expanded metal, failed, as did also the cast-iron stairways. The wood covering of the floors and the wooden nailing strips were burned. The concrete floor is in excellent condition. A few panels collapsed where the steel girders were displaced. The distorted unprotected beams and girders around openings show strikingly the folly of unprotected steel work.

CALIFORNIA CASKET COMPANY'S BUILDING.

The building which was in process of construction on Mission street between Fifth and Sixth streets by the California Casket Company was seven stories in height and had a steel skeleton and floors of reenforced cinder concrete. The self-supporting walls were built on the sides and rear of brick and on the front of brick faced with sandstone, which was spalled by the heat, although there was no stock and little combustible material in the building. The columns

were fireproofed with concrete. The brick protection around many of the columns was jarred loose, and the brick vaults on the first, second, and third floors were badly cracked around the archways of the openings into them, as shown in Pl. XXIX, *A*, a view of a vault in the second story. The stairways were constructed of concrete with steel channel horses and were cracked in a number of places, especially at the landings. Some of the wooden window frames were burned, but the fire was not very severe either in the building or surrounding it, the greatest damage resulting from the earthquake. The partitions inclosing stairways and elevator shafts were of the usual flimsy metal lath and plaster type. The walls were so badly cracked as to require partial rebuilding, especially at the southwest and northwest corners.

CALL (CLAUS SPRECKELS) BUILDING.

The Call Building (fifteen stories besides the dome), corner of Third and Market streets, was one of the best-designed skeleton buildings in San Francisco. It was fairly well braced laterally, and the workmanship was first class. It stood the earthquake shock well because of its excellent foundation, which extended 25 feet below the sidewalk and consisted of a grillage of steel beams embedded in concrete. The main defect was in the fireproofing of the floors and columns, in which terra cotta was used, and the greatest damage to the building was from fire. Although some of the diagonal braces were bent and had apparently been stretched so as to take a permanent set, the general behavior of the structure demonstrates that high buildings subject to earthquake can be erected with safety even on sand foundations.

The floors were of reenforced concrete up to the seventh story and of hollow-tile arches above, topped with cinder concrete. The partitions were principally 3-inch hollow tile, and these failed very generally. The terra-cotta fireproofing around the columns proved ineffective, and although the steel did not buckle, the paint had been burned off the metal. Wood floors laid on wood nailing strips were used in all offices and were all destroyed by fire. The marble tiling and wainscoting of the corridors was either shaken down by the earthquake or destroyed by the fire. The stairways had cast-iron horses and marble treads, most of the latter being calcined. The suspended wire lath and plaster ceilings were generally destroyed because of the lack of proper fastenings. The curtain walls of granite and sandstone were not damaged by the earthquake, but were considerably spalled by the fire.

CHRONICLE BUILDINGS.

The Chronicle buildings, corner of Market and Kearney streets, comprised an old ten-story structure and a new fifteen-story annex that was in process of construction, both shown in Pl. XXX, *B*. The old building consisted of steel beams and protected cast-iron columns, with self-supporting walls, which had a brownstone front up to the second. story and were ornamented with terra cotta above. The floor was of hollow tile, filled with cinder concrete and covered with wood. The cast-iron columns were fireproofed with 3-inch hollow tile, and 4-inch hollow tile was used for the partitions. The terra-cotta partitions and fireproofing entirely collapsed. The building appeared to have stood the earthquake shock, and received its principal damage through the fire. The collapse of the western section of the building was probably due to the buckling of the cast-iron columns.

In the annex terra-cotta hollow tile was used for the floor construction, 4-inch hollow tile for the partitions, and 3-inch hollow tile for fireproofing the columns and girders. The curtain walls were built of sandstone, with terra-cotta trimmings for the front walls of the first and second stories, and brick and terra cotta for the remainder. The building was racked considerably by the earthquake, the front walls developing the characteristic X cracks (a number of which may be perceived by a close inspection of Pl. XXX, *B*), due to a lack of diagonal bracing of the steel skeleton. The tiling failed extensively, the lower webs spalling off and the columns buckling in the southwest corner on the upper floors above the roof of the old Chronicle Building. There was little combustible material in the building, and the trim had not started; a few of the wooden window frames only burned; so that the fire test was not great.

CITY HALL AND HALL OF RECORDS.

The city hall (Pl. XXXI) was a brick building, at City Hall avenue, Larkin street, and McAllister street, consisting of steel floor beams and corrugated-iron arches with cinder-concrete filling. It was wrecked by the earthquake and subsequently gutted by the fire. A prominent feature was a central tower, surmounted by a dome built over a structural steel skeleton. Grouped around the dome were a number of cast-iron columns of half-inch metal filled with brick concrete supported on brackets. Some of these columns in falling broke into small pieces. The brickwork was completely shaken from the central tower. The cement-plastered brick walls were laid in lime mortar of generally poor quality and without adequate tie to the steel work. In some places there was an absence

of any mortar, but in others it was very good, the brick walls falling in large masses and the broken bricks showing the mortar to have been the stronger. The massive architectural ornamentations were top-heavy and lacked adequate bracing. The ceiling was formed of corrugated metal against which the mortar plaster was pressed, with intermediate brick partitions where the span of the beams was too great. The expansion of the corrugated-iron arches by the heat produced a rise at the crown, and the softening of the iron caused the arches to fail; they would have been much stronger without the unprotected corrugated iron. In the treasury department a granite column was badly spalled by the fire. The building was a monument of bad design and poor materials and workmanship, and was not, therefore, of such a character that it could be expected to resist successfully the effect of earthquake or fire.

The damage done to the hall of records by the earthquake was not serious, and consisted of the falling of a small section of brickwork from the third story on the west side and other cracks in the walls. The fire, however, destroyed the contents of the building, leaving only the shell standing.

CROCKER BUILDING.

The ten-story Crocker Building, corner of Powell and Market streets, was a steel-skeleton structure, with hollow-tile floor arches, partitions, and fireproofing for columns and girders. The first two stories of the self-supporting walls were granite, and the remainder buff brick with terra cotta.

On the ninth and tenth floors the light Phœnix columns buckled through the failure of the hollow-tile fireproofing. The fire was only moderate, however, and except on the ninth and tenth floors the steel appeared to be in good condition. The weakness of hollow floor tiles for carrying heavy loads was demonstrated in a number of places where the tile floors had been broken by the fall of safes. The lower webs of the floor tiles had failed over extensive areas. The stairways, with their cast-iron horses and slate treads, were not damaged to any great extent. The floors were topped with cinder concrete and covered with wood in the offices and with mosaic in the corridors.

EMPORIUM.

In the building known as the "Emporium," 825-855 Market street, west of the Academy of Sciences, the first two stories were fireproofed with terra cotta. Slow-burning wooden construction was used above the second floor. As shown in Pl. XXXII, very little of this structure save the exterior walls was left standing.

FAIRMOUNT HOTEL.

The six-story Fairmount Hotel, California, Mason, Powell, and Sacramento streets, was nearly completed, and the only combustible in it was the lumber used in construction. It consisted of a steel skeleton with floors of cinder concrete reenforced with expanded metal. The walls were self-supporting and were constructed of granite backed with brick up to the third floor and of light-colored terra cotta in the upper stories. The ceilings were of the suspended type plastered on metal lath. The original plans called for the columns to be fireproofed with concrete, but because of the greater expense of this material the plans were changed and the expanded metal and plaster partitions were molded around these columns. The result was that even under the moderate heat to which the building was subjected about 40 of the columns buckled, including 23 on the third floor alone (Pl. XXXIV), and the partitions were completely wrecked. The effect of the earthquake shock was principally confined to the west end of the north front. The terra cotta was spalled considerably and the granite only slightly by fire. The exterior damage was not very great.

JAMES FLOOD BUILDING.

The steel-frame twelve-story James Flood Building, on the northeast corner of Powell and Market streets, was constructed with segmental hollow-tile floor arches topped with cinder concrete and suspended ceilings plastered on metal lath. The columns were constructed of Z bars and were filled with common brick to the outer edge of the section and the whole inclosed with 3-inch hollow tile. This tile failed (Pl. XXXV, *A*), although the fire could not have been very severe, for the wooden floor in the offices was only partly burned and there were a number of wardrobes and switch boxes of wood, besides the door and window frames and wainscoting, which were not burned. The stairways, which had cast-iron horses and marble treads, were in fair condition. The corridors were tiled with marble. The stonework was very slightly spalled by fire, and the principal damage by earthquake was a cracking of the sandstone at several of the entrances (Pl. XXXIII, *B*).

GRANT BUILDING.

The lower floor of the Grant Building, at the southeast corner of Seventh and Market streets, was used for a bank, the upper floors for offices. It was eight stories high and had a steel frame with cinder-concrete floors, the beams and girders being of solid concrete. The first story had self-supporting walls of sandstone, and the remaining

stories walls of pressed terra-cotta brick, trimmed with sandstone. Hollow tile was used to fireproof the columns and for the partitions.

The cast-iron stairways with marble treads were damaged but slightly. The hollow-tile partitions were badly wrecked, most of them being thrown down. The building was injured considerably by dynamiting, which partly disguised the damage caused by the earthquake.

HOTEL HAMILTON.

The twelve-story apartment house known as the Hotel Hamilton, on the north side of Ellis street between Mason and Powell streets, was a steel-skeleton structure with floors of reenforced concrete and girders and beams of solid concrete. Plastered wire lath served as a fireproofing for the columns, and the suspended ceilings were of the same material. This construction may be seen in Pl. XXXVI, *B*. Four-inch hollow tile was used in the partitions.

The marble treads of the cast-iron stairway were to a large extent calcined. A number of the columns buckled on the first, sixth, and seventh floors, the wire lath being entirely insufficient. This buckling caused the floors throughout the building to settle. The damage by earthquake to the curtain walls was slight. The sandstone finish of the first four floors spalled but little from the heat; the terra cotta above, however, was considerably spalled.

HIBERNIA SAVINGS AND LOAN SOCIETY'S BUILDING.

The two-story bank building of the Hibernia Savings and Loan Society, on the northwest corner of McAllister and Jones streets (Pl. XXXVII, *A*), was constructed with two street fronts of granite and rear walls of brick. The gallery and a portion of the second floor were constructed of brick and concrete arches. The ceilings and ornamental work were plastered wire lath. The dome was sheathed with copper. The granite fronts, especially around the doors and windows, were badly spalled by fire; other damage to the structure was confined almost entirely to the roof.

HOBART BUILDING.

The five-story Hobart Building, on the north side of Market street near Post street, had bearing walls of brick faced with granite up to the second story and of brick trimmed with terra cotta for the remaining stories. The framework consisted of cast-iron columns with steel girders and beams; the floors of segmental arches of plain concrete. The cast-iron columns were fireproofed with brick in the basement, and with wire lath and plaster on the first floor. The partitions were of 4-inch hollow tile. The ceilings were plastered wire lath attached to the lower flanges of the beams.

The granite columns were spalled practically to destruction by fire, as shown in Pl. XXXVI, *A*. The fire in one section appeared to be very hot and caused a collapse of one of the floors, which was followed by the failure of the other floors of that section of the building.

JACKSON BREWING COMPANY'S BUILDING.

The plant of the Jackson Brewing Company, on the southeast corner of Eleventh and Folsom streets (Pl. XXXVII, *B*), was in process of construction and was wrecked by the earthquake, the damage by fire being but slight. The brick walls were laid in lime mortar of poor quality. The steel beams and girders were supported by cast-iron columns. Many of the various steel members were bolted together with an insufficient number of bolts, the girders and beams resting upon the walls without any tie; the columns, girders, and beams were not fireproofed, and in the eastern half the concrete floor slabs, 6 inches thick, were without reenforcement. Several persons were killed by the collapse of the tower. That this building should have been wrecked is not surprising, as the design was bad and the material and workmanship were very poor.

HALL OF JUSTICE.

A steel frame and floors of cinder concrete reenforced with expanded metal were used in the Hall of Justice, at the corner of Kearney and Washington streets. The earthquake largely wrecked this building (Pl. XXXIX, *A*). The cupola of light steel angles collapsed from the heat after being racked by the earthquake. The walls were laid in lime mortar, and the floor panels were stiffened, as in the Ætna Building, with 5 by ½ inch steel bands. The floors were wood covered and were burned. The suspended ceilings were of plastered expanded metal lath, the partitions of 3-inch expanded metal, plastered, while the columns had a double layer of plastered expanded metal with a 1½-inch dead air space between. The suspended ceilings failed, as shown in Pl. XXXV, *B*, a view taken on the second floor. One of the central basement columns buckled and collapsed 18 inches, presenting the appearance of having punched a hole in the floor. Two of the six-cell prison cages fell through the floors into the basement. The cast-iron stairways with marble treads are in fair shape.

KAMM BUILDING.

The seven-story L-shaped Kamm Building, on Market street, west of the Call Building and adjacent to it on two sides, had a steel skeleton and self-supporting sandstone walls. The floors were of reenforced stone concrete, covered with wood, with hollow partitions and sus-

pended ceilings of plastered wire lath, the steel columns, beams, and girders being also fireproofed with plastered wire lath.

The rear structure collapsed when a number of columns in the basement buckled under the intense heat produced by the burning wall paper, of which there was a large quantity stored in the basement.

KOHL (HAYWARD) BUILDING.

The Kohl Building, on the northeast corner of California and Montgomery streets, which presented a number of interesting features, is of a modern type of steel-skeleton construction, 11 stories in height. The floors were of concrete, reenforced with expanded metal, and the columns were incased with expanded metal, plastered. The partitions were made of hollow tile, with metal-covered frames, doors, and windows. The suspended ceilings were of plastered expanded metal.

The earthquake did but little damage, breaking a few panes of glass and loosening the marble wainscoting. There were also a few cracks in the stone facing at the southwest corner of the first floor. The first, second, third, fourth, and part of the seventh floors were burned, the remainder of the building being undamaged. The structure was surrounded by a series of rather low buildings, and the fire was not severe either on the outside or inside. The character of the inside trim prevented to a considerable degree the spread of the flames. One defect in the construction was in the use of plate glass instead of wire glass for the doors and windows.

MAJESTIC THEATER.

The Majestic Theater, at the corner of Ninth and Market streets (Pl. XXXIX, *B*), although one of the largest and best of the San Francisco theaters, was particularly bad in design. The roof trusses, of about 80-foot span and perhaps 75 feet above the ground, were carried on 18-inch walls insufficiently reenforced by pilasters.

The common brick bearing walls were completely wrecked by the earthquake. The roof trusses over the stage collapsed. The walls still show extensive earthquake cracks, as will be seen from the illustration. The building was subsequently gutted by fire.

MERCANTILE TRUST COMPANY'S BUILDING.

The three-story Mercantile Trust Company's building, on California street east of the Kohl Building, like most of the low structures, appeared to be immune from the earthquake and fire. The principal damage was caused by the falling walls of adjacent buildings, which smashed in the steel roof with its heavy glass and started a fire in the interior. The granite facing around the windows spalled to a slight extent, but the building was not badly damaged.

MERCHANTS' EXCHANGE BUILDING.

The recently constructed modern office building known as the Merchants' Exchange, on California street between Montgomery and Sansome streets, caught fire from the outside and its contents were destroyed. The edifice was 13 stories in height, with steel skeleton, fireproofed with plastered wire lath and reenforced-concrete floors. The floors of the rooms were of wood; the corridors were floored and wainscoted with marble. The fireproofing of the columns consisted of two layers of quarter-inch wire lath with a dead air space between, except those which were bricked into the outside walls. The suspended ceilings and partitions were likewise of plastered wire lath, and the same material formed the walls of the "fireproof" vaults. The curtain walls were of brick on the sides and rear; on the front the first two stories were of granite, the remainder being pressed terra cotta with terra-cotta trimmings. The heat of the fire was sufficient to calcine a large portion of the wainscoting and the marble treads of the cast-iron stairways. Though not completely destroying it, the fire burned the life out of the plaster, all of which will have to be renewed. The rear walls were cracked by the earthquake. The enameled brickwork of the light well (Pl. XL, *A*) also shows earthquake cracks, and is badly spalled by the fire. The stonework was slightly spalled by the heat. The metal frames between the windows opening into the court were buckled, the cinder-concrete fireproofing being insufficient. The terra-cotta trim in the light well was also badly spalled.

MILLS BUILDING.

The eleven-story Mills Building, at the northeast corner of Bush and Montgomery streets, had a steel skeleton with hollow-tile fireproofing and hollow-tile partitions. The floors were also of hollow tile topped with cinder concrete and covered with wood in the offices; the tiling and wainscoting of the corridors were of marble.

The walls were racked by the earthquake. The hollow tile failed and left the steel skeleton exposed to the fire. Just how seriously it was damaged is problematical; four of the basement columns buckled (Pl. XL, *B*), the lower webs of the floor tiles failed over large areas (Pl. XLV, *B*), and the partitions and the marble treads of the cast-iron stairways were destroyed. In the light well the window casings were distorted by heat because of insufficient fireproofing, and the terra cotta, granite, and exterior trim of the wall were badly spalled. Owing to the failure of the floor tile many safes fell through the several floors. The building should be rebuilt.

UNITED STATES MINT.

The massive three-story Government building occupied by the United States mint, at Fifth and Mission streets (Pl. XXXVIII), which was not damaged to any appreciable extent by the earthquake, was inspected in company with the superintendent, Mr. Leach. One of the interior walls was weakened by a break in the sewer which ran under it, and one of the chimneys was cracked at the top. This structure, which is located at the intersection of two wide streets, is built on soft alluvium, but rests upon a substantial pile foundation. The bearing walls were of solid brick faced with granite, the northwest face of which was badly spalled by fire (Pl. XXXVIII, *B*). The floors consisted of brick arches between steel beams, finished in cement. They were supported by cast-iron columns, which were unprotected except where they were incased by the heavy brick wall partitions. The doors and windows were of wood glazed with plate glass, the windows on the first and second floors being fitted with folding inside iron shutters. The roof and northwest side of the third story caught fire from without, but as an artesian well provided an independent supply of water the fire was prevented from gaining a foothold, and the building was but slightly damaged.

MONADNOCK BUILDING.

The ten-story Monadnock office building, on the south side of Market street between the Palace Hotel and the Call Building, was in process of construction and was damaged by the earthquake and by dynamiting in the vicinity, besides being gutted by fire.

The west wall was not erected, as that section was incomplete, pending the satisfactory purchase of the land. The structure had a steel skeleton frame, reenforced-concrete floors, with a ceiling of plastered expanded metal. The columns were incased with two layers of plastered expanded metal, with a dead air space between them. The partitions were 3 inches thick, plastered on wire lath. The floors were topped with cinder concrete and covered with tile in the corridors and with wood in the offices. The corridors were to have been wainscoted with marble also. The building was not adequately braced diagonally. Large areas of the exterior were damaged and will have to come down. Two unprotected columns in the basement collapsed, settling the floors for 7 inches. The building is to be repaired by jacking up the floors and replacing the buckled columns. What effect this will have on the reenforced-concrete floors is problematical. Certainly their factor of safety is reduced, and in the judgment of the writer the building is materially weakened, for the reason that the buckling of the columns, which resulted in the settling of the floor, cracked the floor beams at their points of connection with the

columns. While the jacking up closes the cracks, it can not restore the original strength of the connection, which although not entirely gone has been reduced to a very small percentage of its former value.

MURPHY BUILDING.

The columns of the five-story Murphy Building, at the corner of Kearney and California streets, were constructed of corner angles latticed and filled with cinder concrete, the whole being incased with plastered metal lath, with a dead air space between. The floors consisted of cinder-concrete arches between channels.

This building was completely gutted by the fire, although the structure itself was left in fair condition. The metal-lath ceilings and partitions stood the test fairly well, though some of the partitions were buckled out of shape. A view of this damage on the third floor is shown in Pl. XLI, *B*. The terra-cotta trimmings and the copper work around the bay windows were badly damaged by fire.

MUTUAL LIFE BUILDING.

The nine-story Mutual Life Building, at the southeast corner of Sansome and California streets, was fireproofed throughout with terra-cotta hollow tile, with hollow-tile partitions. The treads of the cast-iron stairways and the wainscoting and tile of the corridors were of marble. The office floors were constructed of cinder concrete covered with wood.

The damage to this building from the earthquake was very slight. The fire in the building, while not severe, was sufficient to cause the failure of the tile fireproofing of the roof trusses, which collapsed from exposure to heat (Pl. XLII, *A*).

PACIFIC STATES TELEPHONE AND TELEGRAPH COMPANY'S BUILDING.

The recently completed eight-story building of the Pacific States Telephone and Telegraph Company, on Bush street between Grant and Kearney streets (Pl. XLI, *A*), embodied many good and a few bad features of construction. The side and rear walls were of brick, and the front was of terra-cotta pressed brick and terra-cotta trimmings. All the walls were self-supporting. The floors were of reenforced concrete between steel beams, and the ceilings for all floors above the basement were suspended metal lath, plastered.

The walls were cracked somewhat by the earthquake, and the pilasters on the exterior were spalled. The girders and columns supporting the floors were fireproofed with concrete and were in excellent shape after the fire. The window protection was excellent; the front was provided with Kinnear rolling shutters, with plate-glass metal-covered windows, while the side windows had

metal-covered sash and frames, with wire glass, and tin-covered sliding shutters. The earthquake racked the front sufficiently to prevent the shutters from working. The heat produced by the burning insulated wire and other supplies was high and protracted. The reenforced-concrete beams of the roof were weakened by heat and will have to be replaced. The concrete in general, however, stood this trial exceedingly well in view of the protracted high temperature. The fire caught through an unprotected rear door in the southwest corner, and the break in the roof made possible a very hot fire, which melted glass and even welded nails. The concrete floors and the column protection were not damaged in the slightest. If the methods of fire protection had been consistent throughout, it is probable that this building would have escaped without damage.

POST-OFFICE BUILDING.

The writer made a thorough examination of the post-office building, on Mission street between Sixth and Seventh streets, in company with J. W. Roberts, superintendent of construction, of the Supervising Architect's Office. This three-story structure rested on a foundation consisting of steel beams incased in concrete, carried through the soft alluvium to a hard gravel, the depth varying from 30 feet at Seventh and Mission streets to 12 and 14 feet at the opposite corner. The building had a steel frame, expanded-metal and concrete floors, and plastered expanded-metal suspended ceilings. All partitions or interior walls were of terra-cotta hollow tile, laid with full joints of Portland-cement mortar, the terra-cotta work being first class in every particular. The corridors were tiled and wainscoted with marble. The exterior walls were of granite and were thoroughly anchored, each stone being fastened to the steel work and doweled and pinned to the adjacent stones. The outer facing of granite is carried on the steel work and is not backed with brick, there being an inner wall of terra cotta, with a dead air space between, which serves as a passageway for pipes, flues, etc.

The ground at the corner of Seventh and Mission streets settled about 5 feet (Pl. XLIII, *B*). The floor of the building was slightly cracked at that point, and Mr. Roberts stated that there was a settling of about 1¾ inches. The outer walls were considerably racked (Pls. XLIII, *A*; XLIV) by the earthquake, many stones having been shaken entirely loose from the steel work in some places, while in others a number of stones were started from their beds, and the anchorage was broken. There were also many cracks, especially in some of the exterior pilasters, which were formed of two steel columns, 12 feet apart, without diagonal bracing, the hollow space being used for heating and ventilating apparatus. These pilasters were badly racked.

The worst damage appeared to be in the interior walls of hollow tile, which were very extensively cracked, especially on the first and second floors. The plaster finish on the hollow-tile partitions strengthened them very considerably. One portion of the mosaic ceilings of the corridors on the main floor was laid in Portland-cement mortar on a flat tiled arch and was badly cracked; another portion, laid in Portland cement against wire lath plastered, was undamaged. In the mail-handling room the end wall was moved out of plumb by the earthquake, and the enameled-brick covering of several columns was shaken off. The only damage done by fire was in the district-court room, in the north corner of the third floor, which caught from without and was burned out, together with two adjacent rooms on the northwest front. On the northeast end of the first floor the exterior stonework was also spalled by fire.

A very considerable amount of damage was done by the dynamiting of near-by buildings, which was so severe as to smash the glass and blow out the window and door frames. In many places the marble wainscoting on the opposite side of the corridor was shaken loose. Probably 20 per cent of the injury done to the building is in the glass, marble, and finish. The building is substantial, and the materials and workmanship are first class.

RIALTO BUILDING.

The eight-story Rialto Building, at the southwest corner of Mission and New Montgomery streets, had a steel frame and reenforced cinder-concrete floors. The partitions were of hollow tile and the ceilings of suspended expanded metal, plastered. The columns were fireproofed with two layers of plastered expanded metal for all floors except the basement, where only one layer was used. The corridors had mosaic floors, and the stairways were of cast iron with marble treads.

The building was considerably racked by the earthquake and was further damaged by fire and dynamiting (Pl. XLVIII, *B*). The fire was only moderately hot, but was sufficient to destroy the fireproofing of two columns in the northeast corner of the basement, so that they failed by buckling (Pl. XLVIII, *A*), causing extensive wrecking of the upper floors. The failure of the column protection was caused by the expansion of a pipe inside of it. The terra cotta around the entrance to the building was cracked by the earthquake.

ST. FRANCIS HOTEL.

The twelve-story St. Francis Hotel, in West Union square, at the corner of Geary and Powell streets, was of a modern type, having a steel skeleton, reenforced-concrete floors, with suspended ceilings plas-

tered on wire lath. The fireproofing of beams and girders in the basement and first floor was concrete; in the upper floors it was wire lath and plaster. The columns of the first floor were fireproofed with concrete, those in the basement with brick, and on the upper floors 4-inch hollow tile was used. On the first floor the concrete was omitted for 18 inches at the top and a cap of plaster of Paris used; this was a serious mistake and might have caused trouble.

The stone was slightly spalled by fire and on the front was slightly damaged by the earthquake. The enameled bricks of the light well were badly spalled by heat. Two columns failed by buckling. The fire was not severe, and the damage was not very great.

SCOTT BUILDING.

The Scott Building, on the south side of Mission street between First and Fremont streets, was a four-story structure with a mansard roof. Machinery sales rooms occupied the two lower floors, printing and lithographing offices the upper. The building was constructed of steel girders and beams, with reenforced-concrete floors, suspended ceilings plastered on metal lath, and unprotected cast-iron columns. The curtain walls were carried on steel work which was unprotected over the windows.

The mansard roof and the upper part of the walls were destroyed by the earthquake. The western section was wrecked by dynamite. The ceilings failed, and the stonework spalled slightly. The fire was not severe, to judge from the appearance of the undamaged naked cast-iron columns.

SECURITY SAVINGS BANK.

The Security Savings Bank, a two-story building on Montgomery street between California and Pine streets, received its principal damage from the falling walls of an adjacent building. The granite and marble front was slightly spalled by the earthquake.

SHREVE BUILDING.

The eleven-story Shreve office building, at the northwest corner of Post and Grant streets, was constructed with steel frame, reenforced-concrete floors, and suspended ceilings plastered on metal lath. The columns above the second floor were fireproofed with 3-inch hollow tile; those below with concrete. This latter protection, as well as the concrete floors, is in first-class condition. The difference in efficiency between the concrete and hollow-tile protection for columns is clearly demonstrated, the former being in excellent shape, whereas the latter failed, resulting in a number of buckled columns.

SLOANE BUILDING.

The seven-story Sloane Building, on Post street between Grant and Kearney streets, had bearing walls of terra cotta, brick and terra-cotta trimmings, and a framework of cast-iron columns and steel beams and girders. The partitions and fireproofing were of expanded metal, plastered, and the floors were of concrete, reenforced with expanded metal. All columns except those in the basement were fireproofed with expanded metal, plastered.

There is every indication of a very hot fire in the basement, which buckled several of these unprotected columns, causing a collapse in the central portion of the building (Pl. XLIX, *A*).

SPRING VALLEY WATER COMPANY'S BUILDING.

The City of Paris Dry Goods Company occupied the two lower floors of the Spring Valley Water Company's building, at the southeast corner of Geary and Stockton streets, the remaining four stories being used for office purposes. The building, a general rear view of which is shown in Pl. L, *A*, had a steel skeleton, the partitions, column protection, and floor arches, the lower web of which spalled off extensively, being of hollow tile. The floor arches were topped with cinder concrete and covered with wood. The columns in the southeast corner of the basement buckled, and the upper stories collapsed. The hollow-tile partitions were in bad condition, and the 2-inch tile on columns failed generally. Where the tile ceilings were unprotected the webs spalled extensively; where there was a suspended ceiling remaining in position the tiles were in fair condition. The cast-iron stairways with marble treads were also damaged. There were a few slight earthquake cracks along the Stockton street side, and the south wall had a vertical crack.

UNITED STATES SUBTREASURY.

The four-story brick subtreasury building, on Montgomery street between Commercial and Clay streets, had rolling shutters on the lower front windows and a combination of wood and concrete floors. The wood burned, causing the collapse of that portion of the building. The remainder of the concrete-floor portion seemed to be in fair condition.

UNION TRUST COMPANY'S BUILDING.

The Union Trust Company's ten-story office building, on the corner of Market and Montgomery streets, was constructed with a steel frame. The front walls of the first two stories were granite; the

remaining walls were of pressed terra-cotta brick, with terra-cotta trimmings. The floors and partitions were of hollow tile, and the girders, beams, and columns were fireproofed with the same material. The floors were topped with cinder concrete covered with wood, except in the corridors, where cement finish was used. The cast-iron stairways had marble treads. The granite walls were spalled around the openings by fire. The hollow-tile partitions failed extensively, and the lower web of the floor tile spalled over large areas. The fire was not intense, and the steel appeared to be in fair condition except on the ninth and tenth floors. The extent of the damage can be seen in Pl. L, *B*, a view on the ninth floor. The steel trusses on the tenth floor were very much distorted by heat, owing to the failure of the hollow-tile fireproofing.

VOLKMAN BUILDING.

The lower floor of the Volkman Building, on the north side of Jackson street between Montgomery and Sansome streets, opposite the unburned block near the appraisers' building, was occupied by a branch of the post-office. The structure was surrounded on the sides and rear by completely gutted buildings, and its escape was probably due to its protected openings. The windows were glazed with wire glass and the sash and frames were metal covered. The rear doors were equipped with Kinnear rolling shutters. A few windows were so badly damaged that they will have to be replaced, but the building was only slightly injured, for the fire did not gain a foothold.

WELLS-FARGO BUILDING.

The six-story Wells-Fargo Building, on the northeast corner of Mission and Second streets, is devoted exclusively to Wells, Fargo & Co.'s express business. It has a steel skeleton, self-supporting walls, and reenforced-concrete floors. The ceilings are of plastered wire lath, as are also the hollow partitions and the fireproofing on the columns. The outside walls are of granite for the first two stories and pressed brick and terra cotta for the remaining stories. The openings into the air and light well were of metal frame, glazed with wire glass.

This building shows, especially in the Mission street front, the racking effect of the earthquake. The marble treads of the cast-iron stairways were considerably damaged by the fire, and the marble wainscoting of the corridors was thrown down by the earthquake. The window frames in the light well (Pl. XLIX, *B*) were warped by the fire, which also spalled the terra-cotta trim.

ASPECTS OF THE FIRE DISASTER.

The San Francisco fire, which lasted three days, was one of the greatest conflagrations of recent times. The loss by fire was greater than it should have been, by reason of the failure of the cast-iron water mains in the city; although the loss must necessarily have been great because of the character of the buildings, 90 per cent of which were frame. This disaster demonstrated that the lessons from the Chicago and Baltimore fires are still unlearned. The same faults in construction continue to be repeated. The only sure way to remedy grave defects of this character is to enact strict building laws which will compel an observance of the essentials for fireproof structures.

The conditions at San Francisco were unusual, and even had not the water supply failed it is doubtful whether they could have been controlled, for the reason that it would have been impossible for the fire department to handle efficiently so many fires at a time, especially as there were so many nonfireproof structures. Large conflagrations demonstrate that there is no such thing as a fireproof building. To label one as such is bad practice, since it gives a false sense of security and induces a relaxing of necessary precautions.

FIRE HISTORY AND RECOMMENDATIONS OF INSURANCE BOARDS.

It is claimed that the recorded destruction by fires in San Francisco up to 1899 was excessive, showing an average loss between two and three times that expected in cities having ordinary fire protection. In every year since 1899, except 1903, although the number of fires increased materially, the average loss per fire remained moderate. In any of these years the number of fires involving losses of $40,000 or more did not exceed two. In 1903 there were ten large fires, each involving a loss of more than $40,000, thus bringing the total up to a high figure; and at each of these fires the greater portion of the loss was to the contents rather than to the buildings.

In October, 1905, a board of fire-insurance experts presented the report of an examination made under the direction of the National Board of Fire Underwriters on the fire-hazard conditions of San Francisco. This report is extremely interesting and shows clearly how a body of trained experts can accurately locate defects and predict the consequences likely to result from them. The criticisms and recommendations embodied in the report are particularly pertinent to San Francisco; and when the conditions prior to the great fire are considered, the conclusion must be inevitable that no other result of these conditions—a general conflagration which swept the city—could reasonably have been expected. Attention was called to the following principal features of construction affecting the fire hazard

in the business district: (1) Bad exposures and unprotected openings; (2) poor construction; (3) an absence of sprinklers or of any of the modern protective devices; and (4) excessive height in nonfireproof structures. It is stated that in the congested district about 2.2 per cent were fireproof, 68.3 per cent were wooden joisted brick, and 29.5 per cent were frame buildings. A very bad feature lay in the fact that a large number of so-called "fireproofs" were surrounded by nonfireproofs. The mixture of dwellings and minor mercantile buildings surrounding the congested-value district also greatly increased the hazard.

The board recommended the municipal ownership of the water supply. They considered the present supply ample in amount for the existing requirements, but subject to a decided probability of local failure in emergencies, owing to faults in the distribution system. They deemed it very desirable to increase the capacity of the existing system and to install at the earliest possible date a separate fire-main system, and recommended that all dead ends of pipe mains be connected with the network wherever practicable. They advised that the system of distribution be equipped with a sufficient number of gate valves, so located that no single case of accident, breakage, or repair to the pipe system would necessitate the shutting from service of a length of main greater than the side of a single block (a maximum of 500 feet) in important mercantile manufacturing districts, or than two sides of a single block (a maximum of 800 feet) in other districts.

The building code was found to be satisfactory on the whole, but the board recommended that it be so amended as to limit floor areas, provide for the protection of exposed openings in fireproof buildings, and encourage the use of modern protective devices and constructions, such as sprinkler equipments, automatic fire doors, wire glass, etc. They recommended that prompt measures be taken to relieve the hazardous conditions in narrow streets by widening the streets or enforcing adequate window protection, or both, and advised that automatic sprinkler equipments be required in all buildings which by reason of their size, construction, or occupancy, singly or combined, might act as conflagration breeders. The potential hazard was considered very severe, in view of the exceptionally large areas and great heights of many buildings and of their highly combustible nature by reason of sheathed walls and ceilings, numerous unprotected openings and light wells, and the general absence of fire breaks, taken in conjunction with the presence of interposed frame buildings and the comparatively narrow streets. These numerous and mutually aggravating conflagration breeders, considered in connection with the almost total lack of sprinklers and general absence

of modern protective devices, and the prevailing high winds, made the probability feature alarmingly great.

They advised that the inadequate force of four building inspectors be at least doubled, and that the building laws be rigidly and impartially enforced.

They found the fire department to be an efficient force, well organized under an exceptionally competent chief, and though weak in powerful engines, otherwise fairly well equipped, the number of engine companies being particularly large.

In their report the board summarized the situation in San Francisco as follows:

While two of the five sections into which the congested-value district is divided involve only a mild conflagration hazard within their own limits, they are badly exposed by the others, in which all the elements of the conflagration hazard are present to a marked degree. Not only is the hazard extreme within the congested-value district, but it is augmented by the presence of a compact surrounding, great-height, large-area, frame-residence district, itself unmanageable from a fire-fighting standpoint by reason of adverse conditions introduced by the topography. In fact, San Francisco has violated all underwriting traditions and precedents by not burning up; that it has not done so is largely due to the vigilance of the fire department, which can not be relied upon indefinitely to stave off the inevitable.

FIRE-RESISTING QUALITIES OF STRUCTURES AND STRUCTURAL MATERIALS.

The fire which has practically destroyed San Francisco has more than fulfilled this prophecy. The destruction was greater than in the Baltimore fire because the fire was hotter, owing, as has been pointed out, to the inflammable surroundings and the unprotected openings, and to the unchecked sway of the flames. The heat was so intense that sash weights and glass melted and ran together freely. In some places the edges of broken cast-iron columns softened, the tin coating in piles of tinned plate volatilized, even in the middle of the piles, and nails were softened sufficiently to weld together. (See also Pl. LI, *A*.) The maximum temperature, lasting for a few minutes in each locality, was probably 2,000° or 2,200° F., while the average temperature did not exceed 1,500° F.

Nearly all the so-called "fireproofs" were gutted and their contents destroyed, the fire damage done to these buildings being fully 60 per cent. The early collapse of protected steel frames owing to the failure of the fireproofing was of common occurrence. The extent of the damage to a building from fire can be determined only after the débris and wreckage have been removed and will then be found to be much greater than was at first supposed. This is particularly true of steel structures in which the effect of fire is partly hidden by the débris.

Of perhaps thirty fireproofs of good height with reenforced-concrete floors, all but two had steel frames. Steel beams and columns were generally protected with metal lath and plaster, cinder concrete, or terra-cotta tile. Practically all floor construction consisted either of hollow terra-cotta tile or reenforced concrete. Ceilings of light angles and metal lath, plastered, suspended from floors, served as additional means of fireproofing, by keeping the fire from coming into direct contact with the flooring material. Steel beams in many buildings had no protection, even where concrete filled, except this subceiling. The lower webs of floor tile came off to perhaps a greater extent than in the Baltimore fire. It is said to be impossible to procure a suitable hard-wood sawdust on the Pacific coast, such as is required in the manufacture of porous terra-cotta tile. The tile used is therefore denser and of poorer quality. The behavior of reenforced-concrete floors was most excellent.

Partition walls were in a very few buildings of brick. As a rule, however, they were either of 3-inch hollow terra-cotta tile or metal lath, plastered.

The matter of column protection is very important, as the number of failures in the San Francisco fire was particularly large, especially in the Fairmount Hotel (Pl. XXXIV). Unprotected cast-iron columns failed as a result of unequal expansion caused by the lugs. A few light cast-iron columns filled with concrete came through without damage, and at the Academy of Sciences (Pl. XXIV, *A*), as already described, cast iron failed around a concrete core, which carried the load. Brick-filled columns gave fair satisfaction, but concrete-protected columns afforded the best results. The question of fireproofing, however, is one of degree, being dependent on the intensity and duration of the fire. A column may be fireproofed sufficiently for an office building, but entirely too little for a warehouse; or a column which may be suitable for the upper stories may fail in the basement, as in the Kamm Building (p. 40). Again, the practice of running piping back of the fireproofing on columns, especially if the fireproofing is of hollow tile, is extremely bad. Many failures were caused by the expansion of such piping throwing off the terra-cotta tile. Concrete is probably the best fireproofing material, because, as shown by experience, its stiffness will enable it to support not only the steel within, if the latter is softened by the heat, but perhaps the structure itself. The following types of column protection were used in San Francisco buildings: (1) Plaster on wire lath, both single and double layers, the latter having a dead air space; (2) single terra-cotta tile; (3) concrete; (4) concrete covered with terra-cotta tile; (5) brick.

Of the fire loss, perhaps 75 per cent was in the trim and ornamental work. Inflammable woodwork in the corridors, doors, and windows proved a source of great loss, and should be eliminated for orna-

mental purposes. The behavior of the metal-covered woodwork in the Kohl and other buildings was satisfactory and immensely better than that of the naked wood. It is certain that a building may be finished and trimmed and even decorated with noninflammable materials. Although the additional security of such materials in case of fire does not appeal to owners and architects as compensating for their extra cost in comparison with wood or other inflammable materials, the building laws should nevertheless compel this type of construction.

The loss in ornamental stonework was particularly great, especially in the case of marble, which in many structures was completely calcined. Brickwork suffered most from the earthquake and least from fire, and sandstone splintered less than granite, which suffered severely, a number of badly spalled columns showing how futile this material is for other than ornamental purposes. Concrete proved superior to brick as a fireproofing medium.

It is estimated that over 80 per cent of the so-called "fireproof" safes failed. Many valuable records and much other property were thereby destroyed. An ordinary fireproof safe was of absolutely no value, and the contents of nearly every one were destroyed. In many office buildings so-called fireproof vaults were constructed of hollow tile or plastered metal lath, being formed partly by the partitions of the rooms, and were so flimsy that they yielded readily to the flames. In Pl. LII can be seen groups of so-called "fireproof safes," many with walls 20 inches or more thick, which failed to serve the purpose for which they were designed. Pl. LII, *B*, shows part of a collection of over 50 of these "safes" whose contents were destroyed. In a number of jeweler's safes silver and other precious metals were melted. The warping of the doors also resulted in the loss of the contents in many vaults, even where they were otherwise well designed. In short, fireproof vaults and safes behaved in the San Francisco fire very much as they did in the Baltimore fire. Little progress seems to have been made toward the production of a satisfactory fireproof safe. The only really fireproof vault is one with brick or concrete walls not less than 10 inches thick. The cement-filled metal safe proved to be a very good type of fireproof. Even in well-designed safes and vaults, great care must be exercised in opening them after they have been exposed to fire. Time should be allowed for the temperature in the interior to become reduced to somewhere near the temperature of the surrounding air, as otherwise the contents may be destroyed by spontaneous combustion on exposure to the air. Pl. LII, *A*, is a view of one of the oldest vaults in San Francisco, that of the old Wells, Fargo & Co.'s Express, which passed the fire test satisfactorily.

The writer is of the opinion that the present commercial hollow

terra-cotta tile is largely, if not entirely, devoid of merit for fireproofing purposes. Even when it is of the best grade and workmanship it can hardly be considered a first-class building material. At a comparatively low temperature the tiles fail, the thin webs spalling from unequal expansion. A more porous tile, with thicker webs keyed together and laid in Portland-cement mortar with tight joints, would unquestionably be more suitable for the purpose. It may be true that in case of repairs after a fire damaged tile of the usual commercial type can readily be detected and renewed. Terra-cotta tiling may, however, allow sufficient heat to pass through it to soften slightly the steel member which it encases and still remain in position, thus hiding the defect. Several examples of this condition were found.

The advocates of terra-cotta tile contend that concrete may be seriously damaged by dehydration without noticeable change in its appearance. While this contention may be justified, it should be noted that any weakness or softness may be as readily detected and repaired in concrete as in terra cotta. Concrete, moreover, has the great advantage of being a nonconductor of heat, and so will withstand a prolonged heat before the damage extends to any great depth; and it usually remains in place, maintaining its protective qualities. The value of a structure or of a method of fireproofing is determined largely by ascertaining what portion of the structure is left available for use after the fire. The word "fireproof" is of course a misnomer, for no building is absolutely fireproof; and the resistance offered to fire is one of degree only, for if the heat be sufficiently high and prolonged, nothing can withstand it. The best materials are nonconductors of heat, having high fusing points. At high temperature concrete loses its water of crystallization, but the depth to which this dehydration goes and the rate at which it takes place are the factors that determine the effectiveness of the material. The heat insulation afforded by concrete is of a high order, and to obtain the best results a sufficient thickness must be applied. This required thickness is naturally a variable quantity; 2 inches, or even 1 inch, may be sufficient for an office building, but would be inadequate for a warehouse. These remarks concerning concrete also apply to all other forms of fireproofing. The prime point on which information should be procured is the thickness of the insulation for proper protection against fire.

Perhaps the most important problem is that of protecting a building from fire from without. To do so means the protecting of all openings and the making of the roof equally as resistant as the other parts of the structure. Buildings should be self-contained—that is, protected against exterior fires and capable of fighting fire from the inside; and in earthquake countries, where the outside water service

is likely to fail through rupture of the steel mains, it is highly desirable to have an independent supply, as from an artesian well, with the necessary pumps and service pipe.

In the matter of fireproofing, certain definite recommendations may be deduced from the San Francisco conflagration, as follows:

1. Exterior openings should be protected by the use of metal frames or metal-covered frames with wire glass, or exterior iron shutters or interior metal-covered shutters, or both exterior and interior shutters.

2. The structural members, especially the columns, should be better protected, preferably with solid concrete; they may be filled with brick and covered with terra cotta or with a double layer of cement-plastered metal lath, with an air space between.

3. There should be a better type of partition, the present plastered metal lath or hollow terra-cotta tile being inadequate. Reenforced-concrete partitions are much more efficient.

4. All combustible trim should be eliminated. The fire loss from this item is high, and it should be so designed as to be replaced readily and cheaply.

5. Attic floors and roofs should be designed to resist fire. In many buildings the roof members were not fireproofed and their failure caused great damage.

6. Buildings should be so arranged that the fire could be confined to a single room.

WATER SUPPLY AND OTHER METHODS OF FIGHTING FIRE.

In connection with the matter of the fireproof construction of buildings above referred to, certain suggestions may be made in regard to private and public facilities for fighting fire, as follows:

1. An independent water supply and other facilities for fighting the fire from either within or without should be provided.

2. Another very important problem, at least so far as San Francisco is concerned, is that of the public water supply. The failure of a gridiron system of cast-iron pipes seriously cripples a water supply, no matter how large may be the storage. It is also evident that greater care must be exercised in the laying of these mains, especially in filled ground or alluvial soil, where failures are likely to occur. A system of by-passes should be provided, so arranged as to permit the cutting out of portions which are broken or otherwise damaged, and some system should be installed for quick repairs under emergency conditions.

3. A high-pressure service operated from the bay, using salt water, would also be an essential feature. This service might necessitate a floating pumping station, as recommended by the National Board of Fire Underwriters.

4. The use of explosives, such as dynamite, for fighting a fire should be greatly restricted and intrusted to experts only, or else abandoned. It is extremely doubtful whether the progress of a fire can be checked by dynamiting in advance of the fire without the removal or thorough wetting of the débris. Such procedure would have been impossible in San Francisco, as the water supply was unavailable and it was impossible to carry away the wreckage. The indiscriminate dynamiting did more harm than good, for the reason that the concussions injured the surrounding buildings, as shown, for example, by the extensive damage done at the post-office. Back firing would have been equally bad, because to apply this method successfully plenty of water for controlling the fire is necessary. A fire stop is the best way of checking a conflagration, and a fireproof structure makes the best fire stop if it has well-protected openings.

GENERAL LESSONS OF THE EARTHQUAKE AND FIRE.

In considering the results of the destruction which was wrought by the earthquake and fire there appear certain salient features from which conclusions may be drawn. In regard to the possibility of the erection of an earthquake-proof structure, it is apparent and universally admitted that it would be impossible to build on the fault line a structure which could withstand the effect of a slip. Furthermore, it is realized that in building near the fault on soft or alluvial soil extra precautions must be taken; for example, location of the San Francisco water mains in ground of this character was unwise, since it is difficult to design a waterworks system capable of resisting the effect of settling of the ground. The importance of proper construction and distribution of the water mains in districts liable to earthquakes is demonstrated by the fact that the greatest damage in San Francisco, fully 85 per cent of the total, was by fire. The action of the earthquake in starting the fires which grew to a great conflagration seems insignificant compared to the breaking of the water mains, which left the city defenseless against the flames.

The comparatively great destruction wrought by the earthquake to structures located on filled ground or alluvial soil has already been pointed out. The destruction in San Francisco was confined largely to buildings located on the alluvium of the flats or on the filled ground of old watercourses. That structures can be built, however, which will satisfactorily meet even such conditions when adequate foundations are provided, extending through the soft material to a solid base, is demonstrated by the behavior of such buildings as the Leland Stanford Junior Museum (Pl. XIV, *A*) and Roble Hall, at Stanford University; the Government buildings (Pls. XXVIII, *A*; XXXVIII; XLII, *B*; XLIII; XLIV), and the Call and other buildings in San Francisco.

The structures which suffered most from the earthquake were—

1. The municipal and county buildings. The greatest destruction was sustained by these buildings, which were generally badly designed and poorly constructed of inferior materials, while the well-built, substantial Government buildings suffered less.

2. Lightly and flimsily constructed wooden buildings. Well-constructed wooden buildings generally withstood the shock, but those that were flimsily built, resting upon posts or equally insufficient foundations, collapsed, even where they were fairly well designed. The essentials of earthquake-resisting power are vertical continuity, adequate diagonal bracing, and first-class foundations.

3. Improperly built brick and stone structures. The brick walls which failed, either by being shaken down entirely or by shattering, were laid in lime mortar with few header courses, and generally had wooden frames with little or no bracing and no tie to the walls. Stone and brick masonry cracked diagonally in the form of an X. Hollow-tile partitions and masonry of brick or stone were similarly cracked, although this injury was small where Portland-cement mortar was used. Where the walls were laid with hard brick, with plenty of headers and in Portland-cement mortar, and were properly tied to the floor and roof members there was little, if any, damage. Chimneys collapsed most generally, breaking about halfway up, and destroyed in part at least the structures upon which they fell. While the evidence was by no means conclusive, it appeared to the writer that brick stacks of circular section proved more substantial than square ones. The stack of the Valencia street power plant, which was of eight-pointed star section, collapsed, the part which remained standing showing cracks at one of two opposite reentrant angles almost to the base (Pl. LIII, *A*). It is quite evident that brick stacks and similar tall structures built of brick or stone without reenforcement against flexure, or without being guyed, are unsuitable for use in countries liable to earthquake shock. They should be constructed either of steel, guyed, or, if self-supporting, of steel or reenforced concrete. (See also Pl. XIII, *A*.)

4. Insufficiently braced and loosely constructed steel structures. In structures which were deficient in diagonal bracing the effect of the earthquake was localized in the piers between openings and curtain walls in characteristic X cracks. In tall structures like the Call Building, the tower of the Union Ferry Building, and others, the diagonal bracing that had been installed proved insufficient, and the diagonals at about the middle distance between the top and base were strained beyond the elastic limit of the material, acquiring a permanent set, which was indicated by a slight buckling. It is assumed that the effect of earthquake shock on diagonal bracing is equivalent to a heavy wind pressure, variously estimated at 30 to 50 pounds

per square inch. The writer believes that the higher figure should be used, because the essential in satisfactory earthquake-resistant design is rigidity, whereby the structure moves as a unit. Unless there should be earthquakes of greater severity than the one under discussion, no fear need be felt for tall buildings. It has been fully demonstrated that a steel frame well braced diagonally upon an adequate foundation successfully meets the earthquake requirements; not even the masonry being injured to any great extent.

Concrete, especially reenforced concrete, because of its great adhesive strength and reenforcing metal, proved more satisfactory than any other material. Its solid monolithic structure produces a successful earthquake-resisting material, inasmuch as it moves as a unit; moreover, it offers a maximum resistance to fire. The great concrete dam of the Crystal Springs Lake at San Mateo (Pl. XI, *B*) gave abundant proof of the substantial qualities of concrete in a mass, for although it lies within a few hundred yards of the fault, it suffered no damage. Solid concrete floors proved satisfactory, though concrete in San Francisco was of a very poor quality, and flimsy concrete stiffened with light metal passed as reenforced concrete. Cinder concrete was used extensively for floors and elsewhere, and was of a very inferior grade. Much of it was high in sulphides, which had a deleterious effect on the embedded material, especially in floors where slight cracks permitted air and moisture to come in contact with these sulphides and the metal. For a proper earthquake-proof structure, everything—the design, the materials used, and the workmanship—must be first-class. Most of the failures resulted from bad design, poor workmanship, and poor materials. If reenforced concrete of the quality described could give such satisfactory results in meeting the extraordinary conditions of the San Francisco earthquake and fire, it is evident that much greater satisfaction would have been given by the use of first-class material.

The causes of the failures in San Francisco may be summarized as follows:

1. The effort on the part of those qualified to design and advise on building construction to meet the owners' demands by planning structures so that they can be erected for the least possible cost, a practice which tends to a departure from the principles of correct design, the result being a structure that will carry ordinary loads, but that fails when subjected to unusual conditions. Such was the case at Stanford University, where the poorly constructed stone-veneered buildings met ordinary conditions, but failed in the earthquake: while the more substantial structures, like the dormitories—one of reenforced concrete and the other of solid stone masonry—survived.

2. Actually dishonest design and construction.

The following requirements should be adhered to in structures for earthquake countries:

1. Location on or near the fault should be avoided.
2. Foundations and superstructures should be so built that they will move as a unit.
3. Wooden structures should be rather heavily framed, with continuity in the vertical members, adequate diagonal bracing, and substantial foundations.
4. Steel structures should rest upon an adequate foundation and be thoroughly braced diagonally. This feature is a most important one, as rigidity is absolutely essential.
5. Brickwork and stonework should be thoroughly bonded with full header courses laid in Portland-cement mortar.
6. Masonry should be thoroughly tied to the steel or other framing members.
7. Buildings should have no unnecessary material in their superstructures, and heavy ornamentation should be omitted.
8. Flimsy floors and partitions should be avoided; reenforced concrete is an excellent material for both.

Professor Omori, chairman of the Japanese earthquake commission, and other earthquake authorities, have stated that great earthquakes are followed by a settled condition in the earth's surface and that there is an interval of fifty or one hundred years during which no earthquakes occur. The general fear which prevailed during the first days following the earthquake has been quieted by these assurances, which have also created a feeling of security that has led to a relaxation of the precautions necessary in the work of reconstruction. The lessons taught by the great calamities such as have befallen San Francisco, Baltimore, Chicago, and other cities are not regarded. It is very probable that the new San Francisco to rise on the ruins will be, to a large extent, a duplicate of the former city in defects of construction.

OBSTACLES TO RECONSTRUCTION OF SAN FRANCISCO.

The actual loss by fire in San Francisco was much greater than in the Baltimore fire, for the reason that many insurance companies have taken advantage of the earthquake clause in the policies and failed to pay their claims, while others without the requisite funds were unable to pay the large claims in full. This failure to pay a very considerable percentage of the fire losses and the delay in adjusting them have proved serious setbacks in the progress of reconstruction.

The new building code is also operating against the best interests of the city. The arbitrary classification of buildings based on the

type of construction is one which will result in more harm than good. Those interested in its preparation directed their attention principally to office and other large buildings, apparently not realizing that the greater proportion of reconstruction will consist of small three or four story buildings. The fact that a structure is built of steel and fireproofed does not make it superior to those representing other types of construction, for poor materials and workmanship may produce inferior quality, whatever the type.

The proposed code discriminates against reenforced-concrete buildings in designating them as class B structures. While not intentional, this conveys the impression that such buildings are next in order of superiority to structures of class A. Class A should embrace buildings so well designed and constructed of such first-class materials that they afford the maximum resistance to fire, and should represent the best method of fireproof construction regardless of type.

That there was only one reenforced-concrete building of the modern type in San Francisco was due in part to the opposition of the labor unions. The exorbitant demands for wages, coupled with the high cost of materials, have proved a serious handicap. The cost of all construction work is excessive at the present time, and business interests will suffer from the shrinkage in value which will follow the fall in price of labor and materials. This policy of the labor organizations is materially interfering with and checking the work of reconstruction.

In addition to these labor difficulties, the questions of widening and extending old streets and opening new ones, for the purpose of carrying out the plans for the new and greater city, are still undecided, and most of the business men are unwilling to begin the work of reconstruction until these points are settled.

STATISTICS AND GENERAL INFORMATION.

The defects of construction which are so strongly condemned by reason of the failure of the structures were no worse than those generally existing throughout the United States. The same defects are common, and it is evident that the same result would follow an earthquake of equal intensity in another part of the country. A moment's consideration will show that the loss of life and property in New York, for example, under similar conditions, would be enormous. The damage to property in San Francisco is estimated at $250,000,000, but this sum, large as it is, is exceeded by the total annual expenditures for new construction in New York.

The loss of life from earthquakes is usually very great. That it did not exceed 500 in San Francisco is explained by the fact that at the time of its occurrence, during the early hours of the morning,

most of the inhabitants were in houses, 90 per cent of which were of frame. Structures of this type withstood the earthquake shock particularly well, which accounts for the minimum loss of life. Had the earthquake occurred four or five hours later, when the people were performing their daily tasks, in offices, schools, etc., or on the streets, the loss of life must have been very great. The writer saw a view of a drove of cattle buried under the ruins of a fallen wall while passing through Mission street, which graphically told the story of what might have occurred had the shock come later in the day. Although the loss of life was small, more than 200,000 people were rendered homeless and dependent on the authorities for even the necessaries of life.

In three days the tremendous area of more than 2,593 acres was burned, destroying entirely 490 city blocks and in part 32 blocks. (See Pls. LIV–LVII.) Of this area, 314 acres constituted the congested district, on which there was $250,000,000 insurance, probably representing a value of at least $500,000,000.

In the Baltimore fire (February, 1904) 1,343 buildings were destroyed, having an assessed value of $12,908,300. In two years these burned buildings were replaced by 570 buildings, whose assessed value is $20,000,000. These new buildings are larger than the old, and the widening of the streets has eliminated 700 building lots. It is expected that when the reconstruction within the burned district is complete there will be fewer than 800 buildings, of which the assessed value will be fully $25,000,000. It is therefore quite reasonable to suppose that the assessed value of the reconstructed San Francisco will be at least double that at the time of the catastrophe.

THE EFFECTS OF THE EARTHQUAKE AND FIRE ON BUILDINGS, ENGINEERING STRUCTURES, AND STRUCTURAL MATERIALS.

By JOHN STEPHEN SEWELL.

INTRODUCTION.

SCOPE OF THE INVESTIGATION.

The following pages contain the matter of a report dated July 5, 1906, to Brig. Gen. Alexander Mackenzie, Chief of Engineers, United States Army, of an inspection made by me of the ruins of San Francisco, in accordance with Special Orders No. 97, dated War Department, Washington, April 23, 1906.

I arrived in San Francisco on the morning of May 8, 1906, and remained until the night of May 19. My orders directed me to investigate the effect of the fire and earthquake on buildings and engineering structures in the territory affected by the earthquake, and authorized me to visit such points in addition to San Francisco as it might be necessary to observe. As soon as possible after my arrival, I called on the various military and civil authorities, and procured from the latter permits authorizing me to enter and inspect the damaged structures.

It appeared that in the territory affected by the earthquake, in addition to buildings of various types, there were the works of the Spring Valley Water Company and fortifications, light-houses, and railroad structures. Some rumors of collapsed tunnels on the coast division of the Southern Pacific Railroad had been circulated in the East before I left Washington. I found on inquiry, however, that no tunnels had collapsed, and whatever damage had been done, except to buildings along the line, had been wholly or partly repaired before I reached California.

Inquiry among engineers and others competent to speak disclosed the fact that the dams of the Spring Valley Water Company were practically not injured by the earthquake. Considerable damage was done to some of their conduits and to the pipes of the distribution system. Inquiry in reference to these items disclosed the fact that a

personal examination would consume a great deal of time. It also disclosed the fact that an examination was in process by competent engineers, and Major McKinstry undertook to get for me a report of the results of this examination. As a matter of fact, I have been allowed to see a copy of such a report made by Charles D. Marx and Charles B. Wing, which the authors prefer not to have published as yet. However, certain essential facts as to the condition of dams, conduits, etc. (see Pls. IX; X, *A*; XI, *B*), are taken from it and embodied further on in my own report; although the photographs and certain other features of the report itself, which seem to be peculiarly the property of its authors, are not submitted herewith. In view of the fact that the results of the examination of the waterworks were promised to me, it seemed superfluous for me to visit the dams and conduits, except as a matter of personal interest, and as my time was very short, I decided not to do so.

The light-houses and fortifications are in charge of competent officers, whose duty it is to report the nature and extent of the damage done to them by the earthquake. As an inspection of the light-houses would have involved a great deal of time, I decided not to attempt to visit them, and made only a superficial examination of the fortifications.

As my own experience has been mainly in the line of fireproof buildings, however, I made a very careful inspection of the ruins of San Francisco itself, and also visited Oakland and Palo Alto, with a view to inspecting damaged buildings at those points. I found, as a result of those trips and by inquiry among competent witnesses, that, with one exception, there was no type of building in the affected district which was not well represented among the buildings of San Francisco. The exception was the concrete work at Leland Stanford Junior University, near Palo Alto, to which specific reference is made on page 113. The greater part of my time, for the reasons above outlined, was spent within the limits of San Francisco itself, and much of it within what had been the congested district of the city.

ACKNOWLEDGMENTS.

Acknowledgment is due to Capt. M. L. Walker, Corps of Engineers, commanding officer at Fort Mason, who not only entertained me at his quarters during my stay in San Francisco, but rendered very material assistance in the way of transportation when needed, and especially in placing at my disposal the services of Private William H. Hughes, of the First Battalion of Engineers, a very efficient photographer, who accompanied me and took such views as seemed desirable for the purposes of my report. I was also much indebted to Maj. C. H. McKinstry, Corps of Engineers, who gave me much

valuable information that made it possible to avoid useless expenditure of time, and who was also of great service in procuring for me the necessary permits from the local civil authorities.

EXTRACTS FROM THE REPORT OF A COMMITTEE OF THE NATIONAL BOARD OF FIRE UNDERWRITERS ON SAN FRANCISCO CONDITIONS.

San Francisco before the earthquake and fire consisted mainly of frame and brick buildings of ordinary construction. A few adobe buildings still remain, but there were not many of these. There were about 45 so-called fireproof buildings in the city, and a small number of so-called slow-burning buildings, modeled more or less loosely along the lines of the New England mills. A fair idea of the general nature of the city, so far as buildings are concerned, is given in the following quotations from a report on San Francisco issued by the committee of twenty of the National Board of Fire Underwriters in October, 1905:

CONFLAGRATION HAZARD.

Potential.—In view of the excessively large areas, great heights, numerous unprotected openings, general absence of fire breaks and stops, highly combustible nature of the buildings, many of which have sheathed walls and ceilings, frequency of light wells, and the presence of interspersed frame buildings, the potential hazard is very severe.

Probability feature.—The above features, combined with the almost total lack of sprinklers, and absence of modern protective devices generally, numerous and mutually aggravating conflagration breeders, high winds and comparatively narrow streets, make the probability feature alarmingly severe.

Summary.—While two of the five sections into which the congested-value district is divided involve only a mild conflagration hazard within their own limits, they are badly exposed by the others, in which all the elements of the conflagration hazard are present to a marked degree. Not only is the hazard extreme within the congested-value district, but it is augmented by the presence of a compact surrounding, great-height, large-area, frame-residence district, itself unmanageable from a fire-fighting standpoint by reason of adverse conditions introduced by the topography. In fact, San Francisco has violated all underwriting traditions and precedents by not burning up; that it has not done so is largely due to the vigilance of the fire department, which can not be relied upon indefinitely to stave off the inevitable.

In another portion of the same report the following occurs:

The principal features affecting the conflagration hazard in the business section are bad exposures, poor construction, lack of proper protective devices, excessive height in nonfireproof buildings, large floor areas, and the large percentage of frame construction present.

The mixed dwelling and minor mercantile section which immediately surrounds the congested-value district, and extends from it in all directions with more or less uniformity, is alarmingly compact.

* * * The security resulting from a combination of redwood and such dampness as exists in San Francisco is regarded by the national board engineers as fancied merely.

In addition to the frame, ordinary joisted brick, so-called fireproof, and mill buildings, there were in San Francisco four buildings of a monumental type, so far as weight of construction was concerned. These were the new city hall (Pl. XXXI), the new post-office building (Pls. XLIII and XLIV), the United States mint (Pl. XXXVIII), and the appraisers' stores, or custom-house (Pl. XXVIII, *A*). The few mill buildings which existed were not of a standard type, according to the report of the National Board of Fire Underwriters. The fireproof buildings had been erected in accordance with the building laws of San Francisco, which provided for three principal types of commercial buildings, known as class A, class B, and class C.

The general requirements for buildings of these classes and for mill buildings are as follows:

BUILDINGS IN FIRE LIMITS.

SECTION 96. Every building hereafter erected within the fire limits shall be constructed in accordance with the requirements of this ordinance for the construction of buildings of either class A, class B, or class C.

BUILDINGS OF CLASSES A, B, AND C.

SECTION 97. Class A, termed "fireproof," or "skeleton construction," shall include all buildings wherein all external and internal loads and strains are transmitted from the top of the building to the foundation by skeleton or framework of steel, and the beams or girders of which are riveted to each other at their respective juncture joints. A building of this class must be constructed of noninflammable material throughout, and all interior constructive metal work, with the exception of the framing for elevators and staircases, shall be protected from fire by brick or terra cotta at least 1½ inches thick, or by plastering three-fourths of an inch thick applied to metal lath. The face of the plastering shall be 1½ inches from the metal. Wood may be used only for window and door frames, sashes, standing finish, hand rails for stairs, and for the upper and under floors and their necessary sleepers. Wood may also be used for isolated furring blocks, but this class shall not permit the use of laths or furrings of wood.

Class B. A building of this class shall be constructed with all its exterior walls and piers of masonry, or of masonry and steel, and all exterior surfaces other than masonry shall be covered with noninflammable materials. All partitions, furred walls, or other plastered surfaces throughout shall be metal lathed. All interior metal work shall be protected as in class A, and in addition the floor and ceiling joists, posts, roof boards, and partitions may be of wood in such places as does not violate the requirements of any section or clause of this ordinance.

Class C. A building of this class shall be constructed the same as class B in every respect, except as to the requirements for interior lathing.

SECTION 98. Limit of height of buildings of classes A, B, and C:

	Feet.
Class A, limit of height	220
Class B, limit of height	100
Class C, limit of height	82

(As amended by Ordinance 1297.)

SLOW-BURNING OR "MILL" CONSTRUCTION.

SECTION 99. A building of the slow-burning or "mill" construction type is a building whose outside walls are built of masonry, concentrated in piers or buttresses, between which is a thin wall containing the door and window openings, and whose floors and roof are constructed of heavy timbers, covered with plank of a suitable thickness; the girders being supported between the walls by posts.

SOME FEATURES OF THE EARTHQUAKE AND FIRE.

AMOUNT OF DESTRUCTION DUE TO THE EARTHQUAKE AND FIRE, RESPECTIVELY.

Within the burned area all frame buildings and practically all buildings with timber floors were totally destroyed, with all their contents. This classification includes mill buildings and those of every other type in which the floor construction is combustible. Practically all the so-called fireproof buildings were gutted, and their contents were a total loss. The average loss on the buildings of class A was, in my judgment, considerably in excess of the average loss on the "fireproof" buildings in Baltimore. This statement can not be made with absolute positiveness, however, in the absence of a detailed estimate of the cost of repairing each building, which I had not time to make. I am quite sure, however, that the damage in San Francisco was greater than it was in Baltimore.

From what was left of the ruins themselves, and from the testimony of competent observers, including engineer officers who were ordered into the business district of San Francisco immediately after the earthquake and before the fire had destroyed the evidences of earthquake damage, I think it is quite certain that the earthquake damage was extensive and severe. There were no available data on which to base an accurate estimate, but I formed a general impression that the damage done by the earthquake alone was at least as great as 10 per cent of the total damage by fire and earthquake combined. The damage from the earthquake, however, was localized in a remarkable degree. In places a group of buildings were almost totally destroyed, and buildings almost in contact with them on all sides escaped practically without damage, although I feel quite sure that many of the wrecked buildings were superior in every way to their neighbors which escaped. Owing to the remarkable variation in the intensity of the shock from point to point, thus demonstrated, the measure of damage done to an individual building is by no means a measure of the excellency or inferiority of its construction. Some specific evidence on this point is presented elsewhere in this paper.

FIRE-FIGHTING OPERATIONS—THE USE OF DYNAMITE.

The fire, of course, completed the work begun by the earthquake. (See Pls. LIV–LVII.) The interruption of the water supply, due

to the breaking of the conduits and mains, left the fire practically in control of the situation. Some attempts were made to stop its progress with dynamite, but from what evidence I was able to obtain I doubt very much whether a great deal was accomplished by this means. It is probable that at one or two points where the fire had become much less fierce its progress was entirely stopped by the use of dynamite, but even this much is not certain. I am personally of the opinion that dynamite might be used so as to check the progress of a conflagration, but it has never been properly applied to that purpose as yet. It seems probable that if a strip of property, a whole city block in depth, extending across the entire front of the fire, were selected sufficiently far in advance to enable it to be completely razed by dynamite before the fire reached it it would prove an effectual barrier, especially if there were water available to keep the ruins thoroughly wet. In the absence of the water the only way to make sure of the result would be to have an enormous number of men ready, as soon as the buildings were demolished, to move the débris to the side nearest to the approaching fire. It is probable that the ruins would be set on fire by the dynamite itself, but with a sufficient number of men, properly handled, the amount of combustible matter along the side next to unburned property might be so materially reduced that the fire would not be able to cross the gap. I rather think that unless such heroic measures are applied the use of dynamite is just as likely to do harm as good in resisting the advance of a conflagration. It will readily occur to anyone at all familiar with such things that to get together the requisite number of men and properly direct their work would require full military control of the situation; otherwise the measures described, while not impossible, would hardly be practicable.

One or two attempts were made, apparently with not a great deal of judgment, to dynamite steel-frame buildings that were on fire. I understand that the explosive was simply placed in the basement loose, practically without any tamping, and detonated. The only result was to knock a few basement columns off their foundations and bring down a portion of the floor construction above. I doubt whether any good results could be obtained by trying to dynamite a steel-frame building as a means of stopping the advance of a fire. If, in a strip of property such as that described above, any steel-frame buildings exist, especially if the frames are protected with any sort of fireproofing, it is probable that more good would result from allowing them to stand, while dynamiting their combustible neighbors.

It would be practically impossible in the time available to demolish a steel frame so completely that all of the combustible débris could be properly handled. It would burn more freely and more disas-

trously after dynamiting than if the building were left intact. A good plan in such a case would be to remove all the combustible contents of the building before the fire reached it, throwing them out, if no other course were open, on the side next to the advancing conflagration. Under such circumstances the average fireproof building, while it might be ruined itself, would probably act as a barrier to the spread of the flames beyond it, although, of course, it could not prevent the fire from working around the sides if neighboring combustible buildings were not removed.

A certain amount of damage in addition to that caused by the fire and earthquake was done in San Francisco by the dynamite used to blow down dangerous walls. More specific data on this point are presented in the detailed descriptions.

TEMPERATURE OF THE BALTIMORE AND SAN FRANCISCO FIRES.

The apparently more complete destruction by fire at San Francisco than at Baltimore immediately raises questions as to the probable temperature of the San Francisco fire. I noted everything coming under my observation which would seem to give an idea as to the probable temperature prevailing, and I am personally of the opinion that the San Francisco fire was appreciably hotter than that at Baltimore. Thus, in places which had been occupied by hardware stores I saw kegfuls of nails with the wood all burned away, but with the nails still standing up in a compact mass, retaining the shape of the keg, owing to the fact that they had been partially welded together. In other places kegfuls of nails which had evidently fallen at least one story, and possibly several stories, into the basement of an adjoining building, had nevertheless retained the form and size of the keg, although some of the nails were loosened. I also saw a number of cast-iron radiators that were partially melted and some cast-iron soil-pipe fittings that had been melted to such an extent that it was not possible to tell what sort of fittings they had been. In some cast-iron columns which had been softened and broken in the fire the raw edges of the break were appreciably rounded and blunted, due to the incipient fusion of the metal. In the basement of an iron warehouse I saw a number of racks of steel bars which had apparently been precipitated from the first floor and which were to a considerable extent welded together. The weld was not perfect, of course, but at some of the points where the welds occurred it would have been impossible to separate the bars without considerable damage.

Glass of all kinds melted and ran freely. Lead sash weights melted and ran out of the window boxes before the timber of the boxes was entirely consumed. Several witnesses, among them an engineer officer, told me that they had observed this phenomenon in a number of places. The sheet-metal cases of typewriters and similar articles of

sheet metal, though they showed no evidence of melting, had been almost completely burned up, so that they were full of holes, and the metal itself presented the same appearance as iron that had been burned in a blacksmith's forge. In the warehouse of the Waterhouse & Lester Company, on Howard street, some racks of steel bars were precipitated into the basement when the building collapsed. These bars were partially welded together by heat. (See also Pl. LI, *B*.) In the ruins of glassware and china stores the glass, as a rule, was completely melted, and many articles of porcelain ware had become softened and distorted in all manner of shapes, indicating a high temperature, as porcelain is made of very refractory material.

All things considered, I am inclined to think that temperatures considerably in excess of 2,000° F. were not at all uncommon in the San Francisco fire, although there were manifestly, in the burned area, places where no such temperature was reached. Very few office buildings were subjected to such intense heat, except here and there in individual rooms, where there was evidence of the storage of records or other combustible matter in large quantities; but the department stores, dry goods stores, and other buildings of mercantile occupancy evidently suffered from temperatures at least as high as 2,000° F. In mercantile buildings these high temperatures seemed to be the rule and not the exception.

EARTHQUAKE- AND FIRE-RESISTING QUALITIES OF STRUCTURES AND STRUCTURAL MATERIALS.

EFFECT OF FIRE ON GOVERNMENT AND "CLASS A" COMMERCIAL BUILDINGS.

So far as resistance to the fire is concerned, the only buildings that presented anything of interest were naturally the monumental public buildings and the commercial fireproof buildings of the better class; that is, practically of class A. The fire did not succeed in entering the mint nor the appraisers' stores. It got into the upper story of the new post-office building at one corner, and cleaned out a court room and its adjoining offices; but it was held at this point, and the post-office building itself was not involved in a fierce conflagration such as that which ruined many of the commercial buildings. The fire got into the new city hall, and succeeded in wrecking the portion which was not ruined by the earthquake.

VAULTS AND SAFES.

In many of the office buildings in San Francisco suites of offices were equipped with vaults, some of which were fairly capacious and provided with doors of more or less efficient appearance, a number of them having the ordinary vestibule, with both inner and outer doors. Where the interior partitions of the building consisted of metal

furring, lathing, and plaster, the walls of the vaults were likewise of these materials. Where the interior partitions consisted of hollow tile, the walls of the vaults were of hollow tile also. Although I examined a great many, I did not see a single vault partitioned off either with metal lathing and plaster or with hollow tiles that preserved its contents. I was informed by some gentlemen, who were apparently connected with the Spring Valley Water Company, that on the top floor of their building a vault walled off with hollow tiles had protected its contents, but that the corner of the building in which it was situated had not been completely gutted, so that the vault did not receive a severe test.

In the Baltimore fire there were a number of vaults walled off with hollow tiles, and all that I happened to see during my inspection of the ruins in Baltimore had failed. The same thing was in evidence everywhere in San Francisco, and it is my opinion that this result could have been predicted with absolute certainty at the time these vaults were built, from data then available. To all external appearances, no doubt, the vaults looked like secure places in which to keep valuables; as a matter of fact, they were the flimsiest kind of shells, not capable of resisting any sort of determined attack from either fire or burglars. The tenant would have been better off without the vault, for in that case he would probably have carried his papers to some other point where they would have had a better chance to escape the fire.

The only vaults I saw that came through a really fierce fire without damage were those built of brickwork (Pl. LII, *A*). Even these vaults did not always protect their contents, however. I saw a number of them opened in which the contents had been totally destroyed. As they seemed to be fairly good vaults, this result was a matter of more than ordinary interest. I therefore carefully examined a number of them and discovered that the fire had gained access through cracks due to settling, or to the earthquake, or else through unfilled joints, due to poor workmanship in the original construction of the vault. It appeared that probably the contents of the building were burning fiercely around the vault before the floor above had burned out or collapsed, so as to give full vent to the gases of combustion. Some pressure must have been generated by the great heat thus confined, and under this pressure the incandescent gases resulting from the fire found their way through the smallest and most tortuous passages in the brickwork. In several cases it was apparent that the contents had probably been ignited by a small tongue of flame (probably not thicker than a lead pencil) penetrating into the vault as a result of such conditions.

A few vaults failed owing to the fact that the outer door warped and pulled away from the frame. Whether this warping could have

been prevented with an adequate number of bolts I do not know, but in an important vault it would seem worth while to have the outer door at least filled in the same manner as the door of a fireproof safe. If it were built in this way it would probably not warp—at least not enough to let the fire in.

To judge from the safes which I saw opened, very nearly three-fourths of the safes in the San Francisco fire failed to protect their contents (Pl. LII, *B*), and as a result the loss of valuable papers and records must have been very extensive.

BEHAVIOR OF STRUCTURAL MEMBERS AND MATERIALS.

The commercial fireproof buildings in San Francisco, in my judgment, suffered considerably more damage than corresponding buildings in the Baltimore conflagration. In the San Francisco fire, for the first time, the collapse of protected steel frames, due to the destruction of the fireproof covering at a comparatively early stage in the fire, was a matter of common occurrence. Practically all of the floor construction in fireproof buildings in San Francisco consisted either of hollow terra-cotta flat arches or of reenforced-concrete slabs, carried on steel floor beams. In a few buildings steel columns and girders were used, with reenforced-concrete beams and slabs covering the space between the girders. Steel girders were more generally protected with metal lathing and plaster, or with solid concrete filling, than with anything else, but terra-cotta covering was also used to a considerable extent. The lower flanges of beams were in some buildings unprotected; in others they were covered with metal lathing and plaster; and in still others (a rather general practice), there was a ceiling composed of light furring angles and metal lathing, fastened below the floor construction and plastered. Most of the steel beams and girders in the floor construction had no other protection for their lower flanges than this furred ceiling, even where the webs were protected by a solid concrete filling.

Columns were generally protected in one of three different ways, as follows:

1. With hollow tiles adapted to either a circular or square section, the webs being about five-eighths of an inch thick, and the total thickness of the tile, including webs and hollow space within, being about 2½ or 3 inches. The tiles were from 12 to 18 inches in length and about 12 or 15 inches wide.

2. With metal lathing and plaster surrounding the column, so as to leave an air space of about 1 or 1½ inches.

3. With a solid covering of concrete from 2 to 4 inches thick.

In addition to this protection the columns in the walls were generally covered with 4 inches of brickwork, and in one building there was a double covering of metal lathing around isolated columns, the

inner covering having one coat of plaster applied and the outer covering having the full two or three coats required for the finishing, as the case might be.

In a general way, practically none of the column protection in San Francisco, except the 4-inch brick covering, was adequate. The coverings of terra cotta and of metal lathing and plaster failed absolutely. Although there were a great many individual columns protected with other coverings which suffered only small damage, the number in which the protection completely failed was so great that the statement is entirely justified that practically all the coverings were wholly inadequate to resist any real fire test. The wall columns covered with 4 inches of brickwork were, except in one building, fairly well protected, so far as I was able to determine. None of the columns covered with cinder concrete suffered any serious damage, but there were not many columns protected in this way. Of the three buildings in which I particularly noticed such covering, two had evidently not experienced any great heat. In the third a column covered with 4 inches of cinder concrete had undoubtedly been subjected to a heat that was very intense. The concrete covering was seriously damaged; the column, however, had not suffered. This case is described on page 79.

Interior partitions in San Francisco were built almost entirely of hollow tiles similar to those used for making square coverings on columns, or else of light metal studs covered with metal lathing and plaster. A few were built of brickwork. In a general way it may be said that practically all the interior partitions that were not built of brickwork were a total loss, being absolutely inadequate. In my judgment, the burning of the contents of a single well-filled office room would have developed in the majority of buildings enough heat to get through the surrounding partitions.

The furred ceilings already described were also very largely a loss. In buildings that had been occupied for ordinary office purposes, probably not more than 20 per cent of the furred ceilings absolutely came down; the remaining 80 per cent stayed in place, with complete loss of the plaster, the metal furring and lathing, however, being in shape to use again with only minor repairs. But wherever the amount of combustible matter was evidently greater than that ordinarily found in offices, the entire furred ceiling—metal lathing, furring strips, and all—came down bodily and was a total loss.

So far as I was able to determine, the earthquake did not cause the collapse of any of the floor construction or partitions in any of the fireproof buildings, but it must have shaken a good many of the partitions badly, so that their destruction by fire was rendered somewhat more easy. The earthquake damage, however, only hastened the result. Partitions of the kind that were used in San Francisco

are not fireproof, and a very hot fire will invariably destroy them, notwithstanding the fact that they are made of noncombustible material. I had rather expected to find that some damage had been done by the earthquake to floors made of hollow tiles or brick arches. That no such damage occurred was a matter of some surprise, and indicates that the vertical component of the undulation was not very great. It is probable that the earthquake caused some cracks to appear in the floors, but I did not see any which could with certainty be ascribed to this cause. It was also a matter of some surprise that some of the partitions were not shaken down by the earthquake, considering the ease with which the fire destroyed them.

So far as fire damage was concerned, the floor systems in San Francisco stood better than any other portion of the fireproof buildings, although they did not stand very well, at that. The lower webs came off from the hollow-tile floor arches in the same way that they did at Baltimore, but to a very much greater extent. The cinder-concrete floor slabs in many buildings were protected for a time by the furred ceilings previously described. Where the ceilings failed at an early stage, or where there had been no such ceilings, the damage to the concrete floor slabs was very apparent. The concrete was dehydrated to a certain extent on its lower surface, and in many of the slabs the reenforcement had become so hot that there was a permanent deflection of greater or less extent, accompanied by cracks on the lower side in the middle of the span.

Just how much damage was done by the fire to cinder-concrete slabs was a little difficult to determine, for the reason that most of the cinder concrete used in San Francisco was evidently a very inferior article in the first place. There was no doubt in my mind, however, that the concrete near surfaces which had been exposed to the fire showed deterioration, as compared with that which had not been exposed to the fire, although it was all so poor that there was not much room for difference in quality. I saw reenforced-concrete floor slabs, some of cinders and some of stone, which were on the point of collapse from heat alone, although they had not quite let go.

I also saw a number of terra-cotta floor arches which had totally collapsed. Some of these showed evidence of damage by masses falling from above, but in others the collapse seemed to have been due to heat alone.

Girder and beam protection was a little more efficient than the column coverings, but it was not adequate. Its weakness was not fully developed, because, in many places where the necessary heat existed, the columns failed first and let down the floors, so that it was not possible to say how much of the damage to the floor members was due to heat alone. In a general way, however, it may be said that girder coverings of metal lath and plaster were wholly inade-

quate, those of hollow tiles suffered serious damage, and those of solid concrete failed a little more commonly than they should, although they were the best of all. Many girders that had been covered with metal lath and plaster were badly warped and deflected, and some wholly collapsed, from the heat alone. Many beams were seriously deflected from the heating of exposed lower flanges.

I was not able to learn that any serious damage had been done to column coverings by the earthquake. In some buildings columns which had not been exposed to much heat happened to be standing with their covering absolutely intact, while another column not far away in the same story of the building and evidently subjected to an intense heat had not only lost its covering, but had itself been practically destroyed by the fire. In no such case was I able to discover any evidence of earthquake damage in the covering that was intact, and there was nothing to indicate that one column might have had its covering damaged by the earthquake, while its neighbor escaped. More detailed information relative to fire damage is presented in the discussion of the individual buildings (pp. 76–108).

The earthquake did a great deal of damage, which could easily be differentiated from that due to the fire. As a rule brickwork in San Francisco was laid in lime mortar or in lime mortar gaged with a small amount of Portland cement. Wherever such masonry was subjected to serious earthquake shocks it was very badly shattered. Much of it came down in the ruins, and much of that which remained in place was reduced to a loose pile, without any adhesion between the mortar and the bricks. The bricks in general were more or less misplaced even where they did not come down, and many of them were broken. Where brickwork was solidly laid up in good Portland-cement mortar, if the earthquake shock induced stresses sufficient to damage it, the damage generally appeared in the form of well-defined cracks, which could have been easily pointed up, so as to leave the wall almost as good as it was before.

Well-executed stone masonry subjected to earthquake shocks showed, in many places, considerable slipping of the individual stones, the adhesion between the stones and the mortar having been destroyed. Here and there, where the strength of the mortar approached that of the stone, the stone itself was badly shattered and cracked. Where the wall ran in the direction in which the undulation seems to have been propagated, it generally showed an **X**-shaped crack (Pl. XXII, *A*), the legs of the **X** crossing the affected area in a diagonal direction. Where the masonry was very good these cracks were the only apparent damage, but where it was not so good the individual stones, bricks, or tiles, as the case might be, had been loosened from their beds and broken, so that the entire mass was shattered, although in many places still standing.

In steel-frame buildings put up in the ordinary way, without any special bracing, most of the earthquake effect was localized in piers between windows, as if a horizontal force had been applied to the floor above, tending to slide it with reference to the floor below. As this effect occurred in both directions, the piers referred to were generally marked with X-shaped cracks, and in addition the masonry was apt to be very much shattered. There seemed to be no general rule as to the place where this shattering effect occurred. In some buildings the piers in the one or two stories near the middle of the height of the building seemed to have suffered the most; in others, the piers nearer to the roof. One tall building, which extended far above its neighbors, was seriously damaged in practically every story above the neighboring buildings.

It was apparent that in some buildings the shock was so severe that probably no structure, however well built, could have withstood it absolutely without damage. It was equally apparent, however, that such great exhibitions of energy were confined to small areas, and that it would be possible to put up buildings in San Francisco which would come through a similar earthquake with very little damage except to individual buildings here and there.

Hollow-tile work seemed to be badly shattered by the earthquake in a great many places. Well-executed stone masonry, as a rule, stood better than brickwork. Brickwork built with good hard bricks, laid in Portland-cement mortar, stood better than that built with inferior bricks or inferior mortar.

Of all the structures which were manifestly exposed to severe shock the concrete buildings at Palo Alto stood best. It would seem to be a general rule that increased tensile strength, even in a brittle material, greatly increased the resistance to earthquake shock. The height above the ground at which the damage was greatest appeared to be largely a function of the distribution of mass in the structure itself, combined with the distribution of the bracing. If the base of a tall steel-frame building were subjected to a vibration tending to tilt it, manifestly some time would be required to set the upper part of the building in motion. As the vibration evidently occurred in both directions, there would be a reversal of motion before the upper part of the building had responded to the first impulse. Under these circumstances there would be established somewhere a center of oscillation, where very severe stresses, due to the acceleration of the superincumbent mass, would be largely concentrated.

It might have been supposed that most of the destructive effect of such action would be manifested at the joints in a steel-frame building; but around the joints are concentrated the ends of the floor beams and girders, together with the floor construction, and at the level of these joints is the only portion of the walls which is per-

fectly solid. The shafts of the columns at about midstory height are therefore less efficiently braced than the portions on a level with the floors. Moreover, it is probable that the play in the connections of the steel work at the floor level would permit a little motion here without any damage, provided, in the meantime, the bracing at midstory, due to the masonry, is sufficient to preserve the structure from collapse; thus the connections would escape without material damage. As a matter of fact, some such action seems to have taken place. There was very little damage at the points where the steel work was fastened together; at least, very little that was apparent.

The failure of the masonry in the piers seems to have prevented the columns from being broken across in the middle or permanently deflected. It is an interesting speculation how near some of the unbraced steel-frame buildings were to total collapse under the stresses above described. In my judgment many of them were a little too near for safety. I saw a number of field bolts or rivets that I thought had probably been sheared by the earthquake, but as to most of them I was not sure that they had ever been in place. In one or two instances, however, the earthquake effect was indisputable.

As it is very difficult to discuss the earthquake effect in a general way, however, it will be taken up further in connection with the subjoined detailed description of the effect of the earthquake and fire on individual buildings in San Francisco.

BEHAVIOR OF INDIVIDUAL STRUCTURES.

ACADEMY OF SCIENCES BUILDING.

The Academy of Sciences building, on Market street, was interesting because of its interior construction. This building had cast-iron concrete-filled columns and Ransome reenforced-concrete floor construction. So far as it was possible to ascertain, no damage was done to the reenforced concrete or to the columns by the earthquake. The building was gutted and the floors considerably damaged by the fire, but the columns were not damaged, and on the whole the building stood very well. A very good view of this building was given in the Engineering News of June 7, 1906, page 623. (See Pls. XXIV, *A*; XXV, *B*.)

ÆTNA (YOUNG, OR COMMISSARY) BUILDING.

The steel-frame structure at the corner of Spear and Market streets, locally known as the "commissary building," because it was said to have been erected originally with a view to furnishing offices for the Commissary Department of the Army, rests upon piles, and suffered relatively small damage from the earthquake. Pl.

XXV, *A*, shows the corner of the building and the subsidence of the street at this point. The inlet at the corner indicates the original level of the street. There was a vault under the Market street sidewalk, immediately behind the wall at the curb line. The basement floor in this vault was of concrete and had a total thickness of 7 or 8 inches. The earthquake caused the earth to bulge up in the portion of the basement under the sidewalk, rupturing the concrete floor and turning it up on its edge, so that where there had previously been a clear headroom of 7½ feet the highest point of the bulge was within 3½ feet of the beams carrying the sidewalk. The columns were of steel, protected with expanded metal and plaster. The girders were of steel and the space between them was spanned by reenforced-concrete construction. The reenforced-concrete beams were formed on the lower edge by a curved piece of flat steel (Pl. XXIX, *B*). The concrete floor construction was damaged by the heat to such an extent that a heavy load of sheet iron on the third floor broke through, though it did not fall through bodily. The expanded metal that was used for reenforcing the slabs from rib to rib evidently got hot and was ruptured at this point.

The cinder concrete used in the floor construction of this building was badly damaged by the heat, although the heat could not have been very intense, as otherwise the ribs, with their exposed metal reenforcement, must have failed. Moreover, the girders did not have their lower flanges protected, yet they remained straight. A great many of the ribs, however, were deflected very considerably, but, owing to the fact that they were curved to begin with, this deflection, due to the fire damage, was not very apparent. The columns themselves were practically uninjured, although the column covering was severely damaged and will probably have to be totally renewed. There were some terra-cotta partitions, terra-cotta furring, and furred ceilings in this building, all of which totally failed. The brick wall at the west side of the building exhibited some earthquake cracks, and at a number of places the brickwork spalled under the heat.

APPRAISERS' WAREHOUSE.

The appraisers' warehouse was a very heavy structure, built on the old-fashioned monumental plan. (Pl. XXVIII, *A*.) It was entirely of brickwork, with some stone trimmings, and the exterior brickwork was laid with full header courses. It was practically undamaged by the earthquake, the chimney even being left standing, and the fire did not get into it. It is probable that the shock at the site of this building was not so severe as it was at some other places, or the chimneys, at any rate, would have been thrown down. The building itself shows a very few slight cracks, which may have been due to

ordinary settling and not at all to earthquake. Mr. Roberts, the local representative of the Supervising Architect's Office, informed me that during the construction of the building there had been some unequal settling, so that one end was about 1¼ inches lower than the other, but that this settling had been at a uniform rate from one end to the other, so that it had caused practically no damage. On the interior there were many solid brick partitions, with some unprotected cast-iron columns. The floor construction was of steel or iron beams and segmental brick arches with a span of 3 to 6 feet.

It is worthy of note that immediately after the earthquake and fire three of the very few buildings in the burned district which were absolutely open and ready for business in every particular were the post-office, the mint, and the appraisers' warehouse. The massive construction used in these Government buildings would appear to have been a very good investment.

ARONSON BUILDING.

The ordinary ten-story steel-frame structure at the corner of Third and Mission streets known as the Aronson Building had terra-cotta column coverings and partitions and cinder-concrete floors, all of which were of the types described in this paper as common in commercial buildings. The building seems to have been occupied for light commercial purposes, and the fire test to which it was subjected was therefore somewhat more severe than that prevailing in office buildings.

A column in the basement was buckled, and two of the columns on the first floor were badly buckled near the ceiling, as shown in Pl. XXVII, *B*. These results, so far as the condition of the fireproofing is concerned, are typical not only of the other stories of the Aronson Building, but of similar work in other buildings throughout the burned district. Some of the work in the Aronson Building was not severely tested by the fire and was still intact. An examination of it shows that it was as well done as similar work in any other commercial building in San Francisco. Where the fire was not very hot this kind of fireproofing protected the steel and suffered not more than 10 or 15 per cent of damage itself; where the fire reached the average temperature the fireproofing suffered a loss of 50 to 100 per cent, and where the fire was a little hotter than the average the total loss of the fireproofing and serious damage to the steel work was not at all uncommon. Damage to fireproofing such as that here described occurred in the James Flood Building, the Emporium Building, the building of the Spring Valley Water Company, the Mills Building, and every other building in which hollow tiles were used.

The buckled column in the basement was about the worst example of this sort of damage that I discovered, although I am inclined to

think that in one or two other buildings in which there was a general collapse of the steel superstructure worse columns than this one could have been found under the débris. The débris was not cleared away while I was in San Francisco, so I had no opportunity to see the condition of many columns that had evidently failed.

The basement of the Aronson Building was divided into several rooms by hollow-tile partitions. The room in which the buckled column was located had evidently contained an enormous amount of paper in some form or other, and the heat generated must have been very intense. The fire broke through the hollow-tile partition which separated this room from the adjacent one, but there was very little that was combustible in the latter, and the column standing there had its fireproof covering entirely intact. Examination showed that the work in this building was neither better nor worse than the average of similar work anywhere else in the San Francisco commercial buildings. A plain and inevitable inference is that wherever such work was practically undamaged the fire test was not at all severe.

In the same part of the basement as that in which the above-mentioned column was situated—that is, under the Third street wall of the building—there were two columns covered with cinder concrete. The concrete covering on one column made a very large and heavy pier; on the other it was about 4 inches thick. It was apparent that the heat in this front portion of the room was not quite as severe as it was farther back, where the buckled column was. Not only was there very much less evidence of fire in the way of ashes, etc., but the general indications pointed to a considerably lower temperature—although the heat at this point was very severe, nevertheless. The larger cinder-concrete pier was evidently damaged to some extent by the heat. The cement had apparently been dehydrated to a depth of one-fourth to three-eighths of an inch on the flat surface, and to a greater depth at the corners. The other pier showed more evidence of intense heat. It stood opposite the middle of the room, where there seems to have been the greatest accumulation of combustible matter. When I first saw this column the cinder concrete was dead and friable to a depth of nearly an inch. How much of this was due to original poor quality and how much to the action of the fire was difficult to determine, but fire damage was very evident. This pier showed on the surface a number of longitudinal cracks running from top to bottom, indicating that there had been a tendency for the concrete to fail and come off under the expansion stresses. At a later inspection a part of the concrete covering of this column had been knocked off, and it then became apparent that the cracks above referred to had extended entirely in to the surface of the column itself, and enough heat had got in to partly burn off the paint along the inner edges of the cracks.

The stairways in this building had apparently been partitioned off by hollow-tile partitions, but these were totally wrecked, and the stairways were in such condition that it was only with great difficulty and by going on all fours that they could be used to reach the upper story. In the west wall of this building I saw the remains of a wire-glass window, with metal sash and frame, which had been practically destroyed by the heat—probably, however, as a result of a simultaneous attack by the fire from both sides. Wire glass seems to have done some good service in other buildings in San Francisco, although in the Merchants' Exchange, as in the Aronson Building, it failed completely, so that a constructing engineer, who had drawn his conclusions entirely from what he saw in the Merchants' Exchange, was disposed to condemn wire glass outright.

BULLOCK & JONES BUILDING.

The steel-frame Bullock & Jones Building was faced with ornamental terra cotta, with hollow-tile column covering and reenforced-concrete slabs which were haunched on the beams, the slab reenforcement apparently not being continuous over the tops of the beams. Some of the floor slabs collapsed, and the column coverings failed entirely. Two columns in the third story had buckled in the same way the columns buckled in the Aronson Building. This building was rather more flimsy even than the average commercial building, and the fire nearly brought it down. Pl. XXVI, *A*, is an interior view showing the buckled columns in the second story. It will be observed that pipes were run up inside of the column coverings. Where similar conditions existed in Baltimore it was maintained by those interested in the particular system of column covering used that the pipes had got hot, expanded, and thrown the covering off. My own opinion was and is that the covering must have failed first, otherwise the pipe would not have become hot. It may be that after the covering had partially failed, the pipe got hot and completed the destruction, but if the covering had been efficient to begin with, there would have been no trouble with the pipe.

A comparison of the conditions in the Bullock & Jones Building with those shown in other views—for example, in the illustrations of the Aronson Building—is sufficient to justify the opinions herein expressed. Pl. XXVI, *A*, shows that one of the panels of the floor system had collapsed. My examination of the Bullock & Jones Building indicated that the reenforced-concrete floor construction was haunched on the lower flanges of the floor beams. The photograph confirms this observation, as will be seen by examining the naked floor beam which appears in the lower left-hand portion of the view. The reenforcement of a floor slab should always be con-

tinuous over the top of the beam; otherwise the construction is nothing but an arch, and develops the thrust to be expected of an arch. Moreover, as a rule, tie-rods are omitted when reenforced-concrete floor slabs are used, and it was naturally to be expected that reenforced-concrete floor slabs of this type would collapse to some extent; the wonder is that they did not collapse to a greater extent in the Bullock & Jones Building. The fire damage to ornamental terra cotta in this building was very conspicuous.

CALL BUILDING.

Of all the commercial buildings in San Francisco, by far the most interesting was that known as the Call (or Spreckels) Building, at the corner of Third and Market streets. This building is remarkable for the care and skill shown in the design of its steel work. It is a steel-frame building, all the walls, floors, partitions, etc., being carried on steel work. It has 15 main stories, in addition to the stories in the dome, or cupola, and rests upon a continuous foundation composed of concrete reenforced with steel beams. The building proper is about 75 feet square, but the foundation is about 90 by 110 feet, and was carried to a depth of about 25 feet below the sidewalk level. A fairly complete and satisfactory description of this building was published in the Engineering Record of April 9 and 16, 1898.

In the first four stories above the street the bents of the steel work adjacent to the four corners of the building on each side were braced with solid portal braces. In addition, eight interior bents were braced with diagonal tiebars from top to bottom. At all junctions of girders and beams with columns knee braces were used. The design of this steel work is well worthy of study by anyone interested in such structures. It is probably, on the whole, the best-designed piece of such work in the United States. Another remarkable thing about it is that the execution was apparently as good as the design. In a number of places where the fireproofing had come off the connections were exposed, and the workmanship here seemed to have been practically as good as it could well be made. I particularly noticed the column bearings, and they seemed to be absolutely close and true. Inaccurate column bearings in building work are so often seen that one is almost justified in saying that they are the rule rather than the exception; but in the Call Building such connections as were exposed to view had been put together with extreme accuracy.

The column covering in this building was of hollow tiles, about 3 inches thick, with very thin webs. Partitions were built of the same material. The floor construction was of reenforced cinder concrete. Some furred ceilings composed of wire lathing and light furring strips were also used. The outer walls were furred with 2-inch

hollow tiles. When I saw the building the column coverings and partitions throughout were either down or so badly shattered that nearly all of them would have to be taken down and rebuilt, and the furring had fallen from many of the outer walls. The chief engineer of the building stated that it was practically undamaged immediately after the earthquake, and that the fire which subsequently gained access did not damage it very much, but that a large part of the ruin of the partitions and column coverings was due to the concussions from the dynamite used in demolishing dangerous walls in the neighborhood.

The hollow-tile covering of the steel work came down pretty generally throughout the building. Whether or not this failure resulted from the fire, close examination of the steel work proved that the tile covering was totally inadequate, because in many places there had been heat enough to burn the paint entirely off the steel and to leave indications of high temperature on the metal itself. Photographs taken of the Call Building during the progress of the fire indicate that the fire was not very fierce, yet, in my judgment, some of the steel members were very close to serious damage as a result of it. So magnificent a piece of steel work deserved better fireproof covering than it had; but, as a matter of fact, the steel itself was observed to be fire blackened in many places. The furred ceilings in this building in general suffered so much damage that they should be taken down altogether. The marble finish throughout, while not absolutely destroyed, was so damaged as to be worthless. The reenforced-concrete floor slabs stood fairly well, but some of the concrete looked as if it had suffered appreciably from the heat.

On the exterior the Call Building showed absolutely no damage from the earthquake except in the story immediately above the main cornice, where, in the parts adjacent to the four corners, a few stones had evidently slipped so that the joints had opened up for possibly half an inch or more. The exterior of the building was faced with the grayish-green sandstone which is used for so many buildings in San Francisco. This stone, wherever the fire struck it, not only spalled very badly, but had its color very largely burned out, so that what remained was a dull and lifeless buff gray, the green having totally disappeared.

Examination of the Call Building from the exterior produced the impression that it was slightly out of plumb to the southeast, but later information showed that this estimate of the direction in which the building leaned was incorrect. Captain Kelly kindly sent a man with a plumb line to verify the observation. He plumbed the building from the tenth floor, as its dimensions were reduced somewhat above this point. He found that the building leans uniformly toward Market and Third streets; at the tenth floor the building overhangs

Market street by 8 inches and Third street by 10 inches. This indicates clearly that it is not safe to trust the eye in the matter of a building out of plumb, because when previously examined—not only once but several times—the Call Building presented the appearance of leaning away from Market street instead of toward it. In my judgment the deviation from the vertical in this building may have been due in whole or in part to the earthquake, but it is not at all impossible that it may have been built out of plumb. With the rigid type of connections used in the Call Building, strict mathematical accuracy of construction at all points would be essential to insure the exact perpendicularity of the building. As this accuracy is practically unattainable, it is ordinarily necessary to accept slight deviations from the plumb line and probably, in the majority of cases, a certain amount of torsion in the frame itself. So far as these deviations are kept within reasonable limits they make no serious difference, and the building is just as good for all practical purposes as if it were perfectly plumb and true.

On the whole, the foundations and steel frame of this building were admirably designed. The bracing of the steel work seems to have taken up the vibration due to the earthquake, so as to preserve the masonry of the outer walls. As long as there is no deflection sufficient to crack the masonry, there can be no doubt that the building is safe. It is a question whether other buildings which were not so well braced, and in which the piers between windows were badly shattered, were not dangerously near collapse, and it may well be doubted whether there is not serious damage to the steel work as it is. This matter could be determined only by uncovering the steel and making a detailed inspection.

The only safe plan in the construction of steel-frame buildings is the one followed in the Call Building—that is, to brace the steel work so that by itself it is able to resist the stresses due to the vibration. The engineer who designed the foundations and steel frame of this building may well be gratified at the admirable manner in which his structure fulfilled its purpose. Had the building been as well designed to resist fire as to resist earthquake, it is probable that the total damage would have been very much less than it was.

CHRONICLE BUILDINGS (OLD AND NEW).

The old Chronicle Building (Pl. XXX, *B*) seems to have been built in two parts—a west and an east wing. The west wing had protected cast-iron columns, rolled beams, and terra-cotta fireproofing. The interior structure had entirely collapsed, apparently from the heat. It was impossible, with the débris piled around it, to determine just what the cause of the failure was, but it was probably

due to the buckling or rupture of a lower-story column by the fire. In the east wing of the old building the terra-cotta fireproofing had suffered, to a considerable extent, the typical damage which is described in connection with the Aronson Building (p. 78) and in the general discussion of the subject (p. 72). Many floor tiles had lost their lower webs.

The new Chronicle Building (also shown in Pl. XXX, *B*) was badly racked by the earthquake from the point where it rose above the neighboring buildings to the top. It seems to have been provided with knee braces tending to stiffen it in a direction parallel to the Kearney street front. In the first story, at any rate, there were some diagonal braces in the steel work of the north wall. The worst damage was to the masonry of the Kearney street front; the shattering of this masonry can be observed by a close inspection of Pl. XXX, *B*. This building was unfinished. It had hollow-tile fireproofing, including partitions. The burning out of the window trim and of whatever combustible matter may have been in the building, caused a good deal of damage to the hollow-tile floors, especially near the windows, where the lower webs came off almost completely.

The old Chronicle Building seems to have suffered very little from the earthquake, notwithstanding it must have acted as a buttress for the new building.

CITY HALL AND HALL OF RECORDS.

The new city hall in San Francisco (Pl. XXXI), together with the hall of records, which adjoins it and which formed practically a part of one and the same structure, was a massive brick building with steel floor beams. This building had corrugated-iron floor arches, leveled up with concrete. There were some naked cast-iron columns where the span from wall to wall was too great for the beams. All interior partitions of any importance were of brick and rather heavy. In the basement and subbasement the corrugated-iron arches were left exposed. Everywhere else there was a ceiling carried on a form of metal lathing consisting of sheets of metal crimped so as to form dovetailed grooves or ribs; the plaster, being pressed up against this lathing and into the dovetailed grooves, was enabled to hold on by the key thus formed. The girders in the building were protected by a wrapping of this metal lathing finished on the exterior with plaster. The brickwork in the city hall was made of a very good quality of common bricks. The mortar appeared to be lime mortar gaged with cement, and was distinctly superior to lime mortar pure and simple. The workmanship was also above the average. The bricks were not as well laid as they might be, yet it was not poor

work by any means. I found a few places where joints were not well filled, but not a greater number of such places than one would expect to find even in fairly good work. On the exterior the building was finished with stucco, which was tinted to imitate the grayish-green sandstone so much used for building purposes in San Francisco.

The city hall was of an irregular plan, as it was built on a triangular lot. The building contained in the western part an interior court, in which a nonfireproof structure had been erected prior to the earthquake and fire to accommodate the fire-alarm headquarters. On the southeast front of the building a little to the east of the center was a rotunda with a tower and dome above it. This tower was built of brickwork up to the base of the upper of two peristyles of free pillars around the outside of the tower. This peristyle was composed of steel columns covered with hollow tiles, so as to form a pillar of circular section with an entasis. The walls of the tower from the base of this peristyle up also seem to have been of hollow tiles. At the base of the dome was a floor composed of terra-cotta flat arches. It was reported that the masonry of the building had been reenforced to a great extent with embedded steel bars for the purpose of increasing its resistance to earthquake. I did not notice any such bars myself, but it was very difficult to get such access to the débris as would have permitted the verification of this point.

In a general way it may be said that the southwest half of the building was practically destroyed by the earthquake. The heavy masonry was thrown down, so that the entire southwest half of the tower was left entirely exposed, the dome standing on the steel work alone. The remaining half of the building showed considerable damage from the earthquake, but the principal damage here was due to the fire. Pl. XXXI gives a fair idea of the earthquake damage in the southwest half of the building.

It will be observed that some of the projecting pilasters on the exterior of the wall were badly cracked. A singular action of the earthquake, as exhibited here and in other places, was the tendency to shear off projecting pilasters even though they were built of the same material as the wall and well bonded to it. In my judgment this action was due to the fact that the earthquake caused the wall to rock slightly sidewise. When it rocked toward the side from which the pilasters projected, the entire weight would be for an instant concentrated on the base of the pilaster in such a way as to tend to shear it loose from the wall, which actually happened in many cases, the wall presenting no other evidence of damage whatsoever. Instances of this damage are pointed out in the discussion of other buildings.

Examination of Pl. XXXI, especially with a reading glass, will show that many of the diagonal braces in the steel work of the tower

were stretched beyond their elastic limit. I found, on personal examination in the field, that many of the wind struts had almost slipped from their seats on the columns. The bolt holes or rivet holes intended for bolts or rivets to hold the struts in place between their seats were not filled. Whether this was due to the fact that they had been sheared by the earthquake or whether they had been omitted in erection, I could not determine definitely. The latter will seem a plausible supposition to anyone familiar with the way in which the average erecting gang does its work. A few of the wind struts had absolutely slipped from their seats and fallen down; but it was not possible to determine from the visible evidence whether this damage was due to the earthquake or to the precipitation of the mass of masonry upon the struts as a result of the failure of the outer walls. Examination of the diagonal tie-rods made it apparent that some of them may have been stretched and bent by the mass of masonry falling upon them, but that others had very clearly been stretched beyond the elastic limit by the vibration of the tower during the earthquake. In inspecting the inside of the rotunda I observed considerable earthquake damage to the tower, including the stretching of a pair of diagonal tie-rods in the dome by the impact of the falling material. The terra-cotta floor at the base of the dome was absolutely intact, so far as could be determined. I made an effort to get out upon the steel work of the tower to climb it, but could only get as high as the gallery in the rotunda on a level with the upper floor of the main building. The means of access to the higher points had been evidently destroyed by the earthquake. The portion of the tower above this point, however, was carefully examined through a very good field glass, which enabled me to see a great many details practically as well as if I had been able to climb the tower itself. Among other things, it indicated very clearly that this terra-cotta floor was of a much better type than those ordinarily put into commercial buildings.

Around a portion of the rotunda there was an inner wall, built of hollow tiles, which the earthquake had so shattered that practically the entire wall would have to be taken down in order to make adequate repair. It will be noted by an examination of Pl. XXXI that the brickwork of the building fell and broke up into large masses. If it had been very poor brickwork it would have broken up, for the most part, into individual bricks, and the fact that it did not do so is proof that it was not of a kind to call for serious censure of the architect or contractor. There was practically no fire in the rotunda of the tower of the city hall. Opposite the main corridor connecting with the portion of the building to the north the varnish on the hand rail in the upper galleries was scorched, but on the main floor

a temporary platform covered with bunting, which had evidently been used on the occasion of some meeting, was practically undamaged, except for the material which had been precipitated upon it.

The main structure of the building itself, to the southwest of the tower, as shown in the foreground and to the left in Pl. XXXI, was badly racked by the earthquake. There was very little damage from fire in this part of the building. Either the vibration due to the earthquake or the impact of falling material removed a good deal of plaster from the walls in the part of the building immediately behind the two columns that are still standing, with the portion of the entablature that they supported. A large part of the building was entirely gutted by the fire, so that, in my judgment, it would cost about as much to remove the débris and restore this building as it cost to put up the building originally.

In the northwest corner of the building there was a pavilion which had a row of free columns still standing. In the middle of the west front of the building there had been a pavilion with a similar row of columns, all of which, with their entablatures, were precipitated into the street. These columns were composed of drums of cast iron with annular rebates which enabled them to be securely seated and centered on each other. The interior of each shaft was filled with broken-brick concrete of a very good quality. The columns were very heavy and massive, and it must have required an extremely severe shock to detach their entablatures from the rest of the building and then to throw the whole mass into the street.

The effect of the fire on the interior of the city hall was very interesting. Some parts of the ceiling remained in place sufficiently long to protect the corrugated-iron arches from damage; in fact, some of the ceiling did not come down at all. Such a case is presented in Pl. XXVI, *B*, which shows the incipient failure of a naked cast-iron column and a ceiling that was evidently on the point of coming down. Where the fire was intense it brought the ceiling down in time to permit serious damage to the corrugated-iron arches and their concrete filling. Wherever these arches were exposed directly to much heat the first effect was to cause them to expand and rise at the crown, which generally resulted in shattering the concrete filling immediately over the crown. Further application of the heat caused the corrugated-iron arch to soften and come down altogether. When it did, the concrete followed it, the portion at the crown being too much shattered to act as a key. In this way the total collapse of large areas of floor construction in the city hall was brought about. The concrete arch would have stood better alone than it did with corrugated iron underneath it; indeed, it is doubtful whether any of the concrete arches would have collapsed but for the damage done by the expansion of the corrugated iron. The concrete was of a very fair

quality and the arches were very heavy. Many of the floor beams were 24 inches deep, and that was consequently the depth of concrete at the haunches. The thickness at the crown seems to have been not less than 5 or 6 inches, and the span between floor beams was not more than 6 or 7 feet. A concrete arch of such dimensions and such span, even though it had been made of very poor concrete, should have stood perfectly well had it been depending on its own power of resistance alone. In a number of places where the floor did not collapse the effect of heat on the exposed lower flanges of the 24-inch beams was sufficient to produce a deflection of 6 or 7 inches on a span of 25 or 30 feet. This result indicates clearly the necessity of protecting the exposed flanges of all beams.

Pl. XXVI, *B*, shows some unconsumed papers about the base of the cast-iron column. These papers came from a vault which opened into this room and the contents of which were charred, but not destroyed; all the combustible contents of the room proper were destroyed. The dark splotches on the wall in the background are due to spalling of the brickwork at the surface under the influence of the fire. This phenomenon was noticed in a number of places in San Francisco, just as it was in Baltimore; but as a rule the spalling did not penetrate to a greater depth than half an inch, and the wall itself was practically as good as before. In the fire at San Francisco, as in every other large fire, the right kind of brickwork proved to be more resistant than any other material.

A good deal of the plaster on the interior walls in the city hall was on wooden furring studs and wooden laths. Why this kind of work should have been done is beyond comprehension. Many of the corridors would have suffered practically no damage but for this one circumstance. As the fire burned out the wooden trim of openings between the corridors and the rooms it gained access to the wooden furring and burned it out behind the plaster, thereby bringing most of the plaster down. There were, however, many square yards still standing, although the wooden furring studs and laths had been burned out behind. There would appear to have been no reason for furring these interior walls; the plaster could just as well have been applied to the brickwork itself. As a matter of fact, in many parts of the building it was so applied, though in other parts the walls were furred with metal lathing and studs. Why a uniform treatment was not adopted is not apparent.

The halls of the building were generally floored with marble tile. Even where the heat had apparently not been very intense these tile floors expanded and came up, and the marble was rendered chalky, while the color was completely ruined.

In this building a number of girders or lintels rested upon stone templates, which were exposed at the face of the wall. All such

templates that were subjected to the heat were badly spalled and shattered, and one or two of them had failed sufficiently to permit the ends of the girders to settle an inch or more. I also noticed a number of places in the walls of the building where the fire had evidently found its way into the interior of unfilled joints through very small and tortuous passages.

The hall of records was connected with the city hall by means of an arcaded corridor. The building was circular and all the floors above the first were pierced so that they practically formed galleries. The beams supporting these upper floors or galleries were of steel, set radially and supported at their inner ends by girders carried on a peristyle of 12 circular cast-iron columns, which had no fireproof covering of any sort. The floor arches were segmental arches of common bricks. The lower flanges of the beams were exposed, but the evidence indicated that there must have been a suspended ceiling of some sort below the fireproof floor construction, although it was impossible to determine its nature. It is probable that it was carried on combustible supports of some kind, which have totally disappeared. As the records had been carried away from this building before the fire reached it the heat within it was not very intense and the interior of the structure was standing in a comparatively undamaged condition, except for finish. The exterior walls, however, were badly shattered by the earthquake. The window shutters were of iron, and if they had remained in place, considering the situation of this building, would probably have kept the fire out. As indicated in the view, however, the earthquake wrenched some of these shutters, with their surrounding masonry, entirely out of the wall, thereby, of course, leaving easy access for the flames.

As previously stated, it is my opinion that to remove the débris and restore the city hall, including the hall of records, to its original condition would cost as much as the entire building cost in the beginning. As it was so badly damaged by the shock it would apparently be wise to remove it altogether and build a structure of another type designed to resist earthquakes.

COWELL BUILDING.

No special interest attaches to the Cowell Building, except that it seems to have been more flimsy than the average. It had unprotected steel work and girders and wooden-joisted floors. The effect of fire on the unprotected steel work is well illustrated in Pl. LI, *B*.

CROCKER BUILDING.

The Crocker Building had a steel frame and hollow-tile fireproofing. Some of the tile arches had totally collapsed, and over large

areas—probably at least 30 per cent of the whole—they had lost their lower webs. There was nothing of special interest in this building more than has been described with other buildings. The damage seemed to be about as great as the average—probably more than 60 per cent.

CROCKER ESTATE BUILDING.

Pl. XXVIII, *B*, shows the kind of damage to ornamental terra cotta which is typical of both earthquake and fire action. This particular view was selected because it was possible to take it from a point near by so as to show the damage in detail. The Crocker Estate Building, a part of which is shown in the view, had cinder-concrete floor slabs, rolled beams and girders, and naked cast-iron columns. The fire was evidently not very hot in this building. The lower flanges of the beams and girders were covered with expanded metal and plaster. The webs of the beams were protected with cinder concrete built out solid from the webs to the edge of the flange. The rear portion of this building and a building of similar construction on the east had largely collapsed, apparently as a result of the action of the fire on the naked cast-iron columns. At this and every other point where exposed cast-iron columns had failed it was often noticed that the heads of the columns broke off and remained attached to girders and beams by means of the lugs and bolts. This result confirms conclusions derived from certain experiments made a number of years ago, to the effect that the lugs, ribs, etc., at the heads of cast-iron columns are the source of severe shrinkage stresses, with consequent weakness in the column.

DEWEY MONUMENT.

The Dewey monument, in Union Square, is shown in Pl. XXX, *A*. Careful examination indicates that the upper stone of the shaft has slipped to the left by an appreciable amount—apparently about an inch. The second stone has slipped about three-fourths as far, and the third stone from the top about one-fourth of an inch. I was informed that there is a steel bar running up through the center of the shaft. This construction, if it was used, explains why the monument was not thrown to the ground, as it otherwise must have been.

EMPORIUM.

The Emporium was a large department store on the south side of Market street, between Fourth and Fifth streets (Pl. XXXII). The only portion of its interior structure which remained had been carried by a steel frame. It is reported, however, that mill construction had been used for the upper stories in a portion of the building. It is also

reported that this building was dynamited three times during the progress of the fire, although I was assured by a policeman, who claimed to have been on duty during the whole time, that this report was not true. Under the circumstances, it is a little difficult to draw a reliable conclusion from the state of affairs in the Emporium. However, examination of the ruins indicated very strongly that much of the trouble was due to the inadequacy of the fireproof protection to the steel work.

Pl. XXXII, *A*, is a general view of the collapsed portion of the building and illustrates the failure of the terra-cotta column covering in various stages. The hollow-tile end-construction arches in the mezzanine floor had collapsed over considerable areas, under the influence of heat alone, as the evidence plainly indicated that nothing could have been precipitated upon them and that they were not subjected to an explosion. A considerable portion of the rear wall of the Emporium, which had been thrown down, probably partly by earthquake and partly by the fire, presented one case of very excellent mortar used in a commercial building. The mortar was better than the bricks, and both were of good quality. The fireproofing in the lower part of the building was quite as good as that ordinarily found in similar structures throughout the country. In fact, it would be easy to point out department stores not so well fireproofed as the lower part of the Emporium.

I have always been of the opinion that the Horne store in Pittsburg, which was the first large fireproof department store to be tested by fire, was really closer to collapse from the heat than is generally believed. After the covering has been stripped from a steel column, the time and heat required to bring it down are not very great. The fact that the covering comes off during a fire is absolute proof that it is wholly inadequate. If the steel column stands up, notwithstanding the loss of its covering, it is due to good luck and not at all to good fireproofing. In the Horne store the covering was stripped from a number of columns; in the Emporium Building the same thing happened, but the heat continued a little longer, and there is no doubt in my mind, after an examination of the ruins, that at least a portion of the collapse was due to the failure of the columns under heat. The floor tiles in the Emporium Building lost their lower webs in large quantities, where the arches themselves did not collapse; and tiles in the column covering which did not come off bodily also lost their exposed webs in considerable quantities. The ruins of the Emporium were in a very dangerous condition, so that a detailed inspection was not practicable; and it is doubtful whether any useful results would have followed, because the fireproofing was of the ordinary commercial type which has often enough been proved inadequate to resist a serious fire.

FAIRMOUNT HOTEL.

The lower two stories of the Fairmount Hotel (Pl. XXXIV) were of concrete. The next story, the first, was built of granite, apparently backed with brickwork, and above that the building was faced with ornamental terra cotta. The earthquake damage to this terra cotta was severe. Neither the granite nor the concrete walls of this building seemed to have suffered materially from the earthquake, but the granite was badly damaged by the fire. The building was surrounded by a wide open space, and the fire must have been very fierce in its vicinity to have ignited it. I was informed that considerable damage was done to the steel work and fireproofing in this building; but as the owners, or at least those in charge, objected to having it inspected, and as it was an unfinished building, I made no examination of its interior. If, under the circumstances, it suffered seriously from the fire, the only conclusion that could have been drawn was that the fireproofing was very poorly done.

JAMES FLOOD BUILDING.

The new James Flood office building, situated on the north side of Market street, opposite the Emporium Building, had a steel frame, segmental hollow-tile floor arches, terra-cotta column covering and partitions, and furred ceilings of metal lath and plaster. The hollow-tile column covering and partitions failed in this building in the same manner as in others, and to about the same extent as in the average building. The lower stories seem to have been occupied for mercantile purposes, and here the fire damage was greater than it was above. Pl. XXXV, *A*, is a view taken in the first story of the Market street wing. The second and third columns from the front are slightly buckled to the right. They were covered with hollow tiles in about the same way as the columns shown in the Aronson Building. The columns in the James Flood Building were Z-bar columns and were filled in solidly with brickwork, in addition to the hollow-tile covering shown in the view. In my judgment, this construction was the only thing that saved the Market street wing of this building from collapse, because there was every evidence that the columns which were found slightly buckled had reached a dangerous temperature, and would probably have come down and wrecked all of the building above them had it not been for the stiffening effect of the brick filling.

Pl. XXXIII, *B*, shows a doorway in the west front of the James Flood Building illustrating the damage by earthquake to the sandstone piers. The stone used in this building was the same grayish-green sandstone that is described in connection with other buildings,

and at each principal entrance there was a groined-arch ceiling made of it. These ceilings were so badly cracked and damaged that they will probably have to be taken down and rebuilt.

GRANT BUILDING.

The structure at Seventh and Market streets known as the Grant Building illustrated the capricious variation in intensity of the earthquake shock within short distances. This building was separated from the post-office by a very narrow street, hardly wider than an alley. The building had cinder-concrete floor slabs, furred ceilings in the upper stories, and terra-cotta partitions. Although it was a commercial building of very ordinary type, it was only slightly damaged by the earthquake, but was gutted by fire. It was entirely outside the area of surface disturbance, the streets in its vicinity showing no signs of settlement or upheaval. The fire was not very hot apparently, but was just about able to take the plaster off the under part of the floor construction without seriously damaging the latter. The terra-cotta partitions were all down. There was no evidence of superiority of construction, however, as everything pointed to moderate tests by both earthquake and fire.

HALL OF JUSTICE.

The Hall of Justice was one of the municipal buildings which was seriously damaged by the earthquake. A general view is shown in Pl. XXXIX, *A*, but does not bring out the damage that really occurred. In the basement of this building was another example of buckled columns. The columns were covered with expanded metal and plaster. This covering failed at a point near the floor, and the columns buckled and sank, producing the same effect as if they had been punched into the ground. The column coverings throughout this building failed very generally from the fire.

KAMM BUILDING.

The Kamm Building was situated on Market street, west of the Call Building. The rear portion was extended eastward by a short ell, so that it was wider than the front. It was occupied in the first story and basement by a wall-paper establishment. The columns were protected by metal lathing and plaster.

The burning of the wall paper in the basement caused general buckling of the basement columns to such an extent as to result in the collapse of all the interior framework of practically the entire rear portion of the building. A good view of this building is to be found in the Engineering Record of May 26, 1906, on page 645.

KOHL BUILDING.

The Kohl Building was of steel-frame construction faced with the grayish-green sandstone which is referred to so often. It had reenforced-concrete floors with furred ceilings and partitions of metal lath and plaster. The window frames and sash were metal covered, and there was very little combustible matter in the finish. The doors, with their frames and jambs, were of wood covered with sheet metal. It is manifest that this building was not subjected to very intense heat, as the windows above the fourth story were unbroken and the stone was comparatively undamaged. The first, second, and third stories were burned out, and there was some damage in both the fourth story and the attic.

The metal-covered doors in this building, however, prevented to some extent the spread of the fire within the building itself, so that where one room burned out, the fire coming in through a front window, an adjacent room was not burned because of the resistance offered by the door. The building could hardly have been subjected to a very fierce heat, however, for, if it had been, the light partitions would have failed, in which case the metal-covered doors would have been of no avail. Where the heat was really intense, the wood of doors, frames, and windows burned out under the metal anyway, but of course the metal covering delayed the ignition of the wood and later prevented it from burning freely.

MERCHANTS' EXCHANGE BUILDING.

The structure known as the Merchants' Exchange was a steel-frame building with Roebling cinder-concrete flat floor slabs, double wire-lath and plaster protection for the columns, and partitions made of light furring irons, wire lath, and plaster. In some places wire lath and plaster were applied to both sides of the furring strips; in others the furring strips with the wire lath were simply plastered on both sides. This was one of the buildings in which the vault walls were made of the same materials as the partitions. Every vault in the building failed. All the partitions in the building were a total loss; not only did the plaster have to come off, but the metal framework had to come down also. The floor construction had a furred ceiling below it. The plaster had come down because of the heat on nearly all the ceilings, and probably as much as 20 per cent of the furring rods and wire lathing were down.

Large areas of the face bricks were shaken from the wall of this building, owing to the fact that they were laid without bond. The rear wall was also damaged by the earthquake. The adhesion of the bricks and mortar seemed to be largely destroyed throughout the wall,

without, however, producing any very large cracks. It is doubtful whether the wall is really safe in its present condition. On the inside of this building some of the wall columns were covered with 4 inches of brickwork projecting from the inner face of the wall as a pilaster. Some of these brick coverings had cracked almost entirely away from the main walls, besides being cracked vertically at other points in a manner similar to the cinder-concrete column coverings in the basement of the Aronson Building described on page 79. The brickwork in these places seemed to have been rather below the average in quality. It is not entirely certain whether the fire or the earthquake caused the cracks, but all the columns seem to have been uninjured, although the brickwork of one or two was so badly damaged that it ought to be taken down and rebuilt. Some enameled bricks were practically ruined by the fire, which stripped off the enamel face (Pl. XL, *A*).

MILLS BUILDING.

The large steel-frame Mills Building was without special bracing. The floors were of hollow tiles on the end-construction system, and the remainder of the fireproofing was likewise of hollow tiles. The tile arches lost their lower webs to a great extent, and some of them collapsed, apparently from heat alone; the column coverings failed very generally, and the girder coverings to a somewhat less extent (Pl. XLV, *B*). One basement column buckled under the action of the heat (Pl. XL, *B*). The conditions in the Mills Building as to column coverings and partitions were similar to those in the Aronson Building.

UNITED STATES MINT.

The mint was an old-fashioned monumental structure with granite walls and segmental brick-arch floor construction, carried on iron beams. A general view, showing the southwest front, is presented in Pl. XXXVIII, *A*. The building seems to have been practically uninjured by the earthquake, the only damage visible being at the base of the right-hand brick stack. It is probable that the shock at the locality of the mint was not so severe as it was at the new post-office building, although the two are only a few blocks apart; yet the result may be an indication that the solid old-fashioned monumental walls with the stonework solidly backed up by brickwork constitute after all one of the best types for resisting earthquake shocks.

It is somewhat surprising that the brick stacks were not overthrown, but I am informed that the thickness of the masonry in these stacks was very great, which probably explains their stability. The northwest (Pl. XXXVIII, *B*) and northeast faces of the mint were

considerably damaged by the fire, but the fire was kept out of the building proper by means of water from an artesian well equipped with fire pumps, located in the building.

MONADNOCK BUILDING.

The structure known as the Monadnock Building was an ordinary steel-frame office building, which was in process of erection. It was badly racked by the earthquake. Every one of the piers in which the earthquake cracks appeared was so badly shattered that no repairs short of tearing down and rebuilding would suffice. As a matter of fact, it is probable that adequate repairs to the masonry in the front wall of this building would involve reconstructing more than half of it. It would appear that there must have been rather severe vibration to shatter the brickwork so badly. Whether the steel escaped injury is a question of considerable interest, which can not be settled until the masonry covering is taken off.

MUTUAL LIFE BUILDING.

The Mutual Life Building was a steel-frame structure of the same general type as the Mills Building, and it suffered in the same general way, though possibly not quite so much. Some of the floor arches had collapsed, apparently from falling weights of some sort. (See Pl. XLII, *A*.)

PACIFIC STATES TELEPHONE AND TELEGRAPH BUILDING.

The Pacific States Telephone and Telegraph Building, on Bush street, illustrated the tendency of the earthquake to shear off projecting pilasters (Pl. XLI, *A*). This building had a steel frame, stone-concrete floor arches, furred ceilings above the basement, and concrete column and girder coverings. The front windows were of plate glass in metal-covered sash, with rolling steel shutters on the outside. The side and rear windows were of wire glass in metal-covered sash and frames, with sliding tin-covered wooden shutters on the inside.

The window protection seems to have prevented the entrance of fire from the outside, but in some other way an interior fire was started which completely gutted the building. The interior fire practically destroyed the plate glass, but not the rolling steel shutters. It seriously damaged the tin-clad shutters, but did not damage the wire glass appreciably. Had the interior fireproofing been as efficient as the window protection it is doubtful whether this building would have been burned out, for the interior fire should have been confined to the place of its origin. For these probable facts as to the

history of the fire in this building I am indebted to S. A. Reed, consulting engineer for the committee of twenty of the National Board of Fire Underwriters. Mr. Reed states, however, that the history of the fire here must be largely surmise, because reliable evidence was not obtainable.

This company had also a building with reenforced-concrete floor construction and wire-glass protection for its windows for one of its branch exchanges. The exposure of this building was probably not very severe. It was three stories high and the fire got into the upper story and cleaned it out; but the floor construction prevented the fire from extending into the stories below, which suffered practically no damage to structure or contents. A part of the third-story wall was thrown down either by the earthquake or by some other means, and this damage may have opened a way for the entrance of the fire.

PALACE HOTEL.

All of the interior and the exterior walls of the Palace Hotel, on the south side of Market street, were built of brickwork. It is reported that the brickwork was reenforced with embedded iron bars. The structure stood remarkably well, and there is little indication of earthquake damage. The building was nonfireproof, and was, of course, completely burned out, but the walls still stand almost as good as ever. (See Pl. XXX, *B*.)

POST-OFFICE BUILDING.

The steel-frame and granite post-office building (Pls. XLII, *B*; XLIII; XLIV) was carried on isolated grillage foundations, each column having its own footing. The diagonals of the building ran nearly north and south and east and west, the south corner being at Seventh and Mission streets. To the south and west of Mission street was an elongated, narrow, curved area in which the earthquake damage was very severe. It was commonly reported that this area, which was not far from the south corner of the post-office building, was a stream bed or ravine that had been filled within the recollection of the older inhabitants of San Francisco. Through the courtesy of J. W. Roberts, the local representative of the Supervising Architect's Office of the Treasury Department, I was enabled to make a detailed inspection of the building, and he also gave me very complete information as to the history of the building and the causes of the various items of damage which were in evidence at the time of my inspection. Mr. Roberts, who is evidently a cool and accurate observer, seemed of the opinion that the material under the building was a natural deposit, and not an artificial fill. But toward

the south it was not of a nature to inspire confidence in its carrying power at the depth shown on the foundation plans. He accordingly obtained authority to lower the footings wherever the material at the depth shown on the plans seemed unreliable, so that the footings of the south half of the building were lowered—some of them, as I remember his statements, to a depth of 20 feet or more below the basement-floor level. At any rate, he carried them to a point where the material, in his judgment, was sufficiently hard and compact. All this underlying material is very sandy; but at considerable depths, I understand, gravel appears, and the combination is almost as hard as hardpan.

The walls, floors, and all parts of the post-office building proper are carried on the steel frame. The outer walls consist of a granite facing, carried on the steel work at each floor level. The granite is not backed up in the usual way, the backing having been omitted to save weight. Some distance behind the granite an inner wall was built of hollow terra-cotta blocks. The space between the granite and the terra cotta was used for the passage of pipes, air flues, etc. The granite was heavily anchored to the steel work. In a number of panels of the steel work corner braces made of a pair of channels were used, and they were fastened as far down on the columns and as near to the center of the wall girder that spanned the space between the columns as the window openings would permit. There was also some portal bracing in a part of the building over which it had been intended to erect a tower. This intention was afterwards abandoned, but I understand the bracing was in place. In a general way, panels of the outer wall in which the corner bracing was used suffered less than adjacent panels—especially in projecting pavilions, where there was no bracing.

Practically all the interior walls of the building above the basement were built of hollow tiles. The tiles were of excellent quality, with webs nearly 1 inch thick. The floor and roof construction was of clinker concrete, reenforced with expanded metal. Suspended ceilings of metal lath and plaster were very generally used. In the mail-handling room there were a number of isolated columns filled solid with clinker concrete and covered with 4 inches of enameled brickwork. The column covering was circular, the bricks having been made radial for this purpose.

The lower part of the column, however, was incased in a circular cast-iron covering made in halves and put together around the column. This casing took the place of the enameled brick up to a point above which injury from blows and abrasion was not likely to occur. There were also in the mail-handling room a number of circular shafts of enameled brickwork, with stairways inside, leading to the inspectors' galleries. The corridors of the building and the

more important rooms had a great deal of expensive and beautiful marble finish; there was much marble-mosaic ceiling work, and the finished woodwork was of extraordinary richness. On top of the buildings were a number of chimneys built of granite blocks with terra-cotta linings.

All the materials entering into the construction and finish of this building were the best of their kind, and the workmanship, under the efficient supervision of Mr. Roberts, was as nearly perfect as it is possible to make it. I have never seen work better done, and have rarely seen it so well done. To one who knows and appreciates good work it is a continual pleasure to see everywhere in the San Francisco post-office the record of sleepless vigilance and skilled labor. Where the structural parts were laid bare by the damage due to the earthquake, the same story was told by the minutest details as well as the roughest parts of the work—everything was the best of its kind. It is therefore of great interest to study the effect of the earthquake on this structure, for the care with which it was built must have made it fully as good as its designers could have hoped. Moreover, I am inclined to think that it received a more severe shaking than any other building in the congested district of San Francisco that was at all comparable with it. The city hall was badly racked, but, to judge from the condition of the adjacent street surfaces and the surrounding ruins, the shock was much less severe than that to which the post-office was subjected. For instance, there was a partially erected steel frame (Pl. XLII, *B*) on the southwest side of Seventh street, near the post-office. Before the earthquake all the columns were plumb and in true alignment. As a result of the shock there was a lateral shifting of the column bases—the relative movement being almost 2 feet in some places—at the cellar-floor level. The basement walls of the incomplete building were also shifted horizontally; at the east corner, where the walls had met at a right angle, they had been ruptured by a vertical crack and moved laterally in such a way that the angle between them was reduced to about 75°, as nearly as I could estimate it without taking measurements.

The south corner of the post-office building is shown in Pl. XLIV, *A*. Mr. Roberts states that accurate measurements show that the building proper settled a little at this point, but not more than one-eighth inch relative to other parts of the structure. The general appearance of the building bears out this statement. The result is remarkably gratifying when the great extent of the near-by surface disturbance on Mission street is considered. The street went down about 4 or 5 feet at this point as a result of the earthquake (Pl. XLIII, *B*). The molded granite shelf surrounding the building, shown with small timber props under it in Pl. XLIV, *A*, was set into a rebate in the main wall of the building. When the sidewalk and

the supporting granite curb settled away from the shelf, it remained in position, as a cantilever, but the props were put under it to keep it from being broken. In the basement no evidence of the earthquake could be found, except a few insignificant cracks in the concrete floor, which Mr. Roberts says were not there before the earthquake.

On the whole, I think it is fair to say that the post-office was subjected to an extraordinarily severe test. About half of the chimneys were thrown down. One of them either rocked on its base or was thrown upward far enough to cause the counterflashing, which lapped the flashing about 3 inches, to clear the flashing and come down inside of it. The chimney remained upright, but with a slight horizontal displacement. In the exterior walls a good many stones were started from their beds, and some were cracked. Two or three fell from the wall. At least one anchor was exposed, and it had been broken. Whether the steel work was damaged or not could not be determined, as it was not sufficiently exposed. The damage to the exterior walls is fairly well shown in Pls. XLIII, *A*, and XLIV.

Pl. XLIII, *A*, shows damage on the southwest side of the west corner of the building; the surface of the window reveal and the adjacent return of the upper molding on the sill, at the point indicated by the arrow, were separated at least three-fourths of an inch, yet during the earthquake they were jostled together with sufficient force to abrade the reveal and spall the sill. That this effect should have taken place without shattering all the masonry around the window opening is one of the many inexplicable phenomena that seem characteristic of earthquakes.

The two sides of the pavilion on the Mission street side at the east corner showed cracks in the masonry and a disturbance of the sidewalk. A window arch on the northeast front, where the outer wall of the mail-handling room adjoins the main building, was damaged (Pl. XLIV, *B*). The building is U-shaped in plan, the mail-handling room being in the court and closed in on the northeast by a wall. This wall was seriously shaken and was shored up at the time of my inspection.

With the exception of one window at the north corner, the exterior masonry of the building practically escaped damage from the fire. According to Mr. Roberts, the damage on the northwest front was somewhat increased after the fire as a result of the demolition of some neighboring walls by dynamite because of their dangerous condition.

On the interior some of the marble slabs used for dadoes and wall coverings were shaken off by the earthquake, and some marble columns used in connection with ornamental mantels and doorways were thrown down.

A great many marble slabs were thrown down by the concussion due to the dynamiting of dangerous walls at Seventh and Market streets, less than half a block away. The damage to marble finish from this cause was much greater than that due to the earthquake. Although the slabs brought down by the dynamite may have been loosened by the earthquake, they could have been taken down and reset if the dynamite had not caused their total loss. In one sense much of the loss was irreparable, for adjacent slabs were beautifully matched by being sawed from the same block and then so set in groups of two or four that the veining was symmetrical about the joints. Where one slab of a group was destroyed the only way to restore the finish to its original beauty would be to renew the whole group. In addition to injuring the marble finish, the dynamite did much damage by blowing windows, transoms, and doors from their frames, and by blowing panels out of doors and glass out of windows. With the kind of woodwork used in this building and with plate glass in all the windows, this item of damage was very heavy. Débris from the demolished buildings, also, was thrown across the street and came down through one or two skylights in the post-office building. It was only owing to good luck that some of the employees were not killed or seriously injured. As it was, the interiors of one or two expensively finished rooms were almost wrecked. All the items of damage which Mr. Roberts ascribed to the dynamite were of the same general type as those due to the concussion in mortar batteries, etc. The chief engineer of the building stated that he and some of his subordinates, although down in the basement, were thrown to the floor by the force of one of the dynamite explosions, and that the electric lights were extinguished for several seconds, although the engines kept running. Probably the concussion lifted the brushes from the commutators of the generators. It seems probable, from what evidence I was able to gather, that at first the dynamite was used in rather large quantities without tamping; but later it was used in a more tentative way and tamped with sand bags. By this policy those in charge of the later blasting operations finally got the work down to a system whereby a wall was brought down within a distance of 20 feet from the base on either side without any dangerous hurling of débris beyond that distance. So far as I was able to learn, after the work had reached this stage no one noticed any damage to neighboring structures, and, in fact, very few people were aware that blasting was in progress.

Some of the mosaic ceilings in the post-office building were planted on a terra-cotta base, others on a furring of metal lathing and plaster. The former were seriously damaged by the earthquake, but the latter remained intact. As previously stated, the interior walls

in the post-office were built of 6-inch terra-cotta blocks, with webs nearly 1 inch thick. They were beautifully built, every joint being absolutely filled with cement mortar that was much harder than the tiles, though the latter were of exceptionally good quality. None of these walls were thrown down, but many of them showed the intersecting diagonal cracks that are characteristic of earthquake action. The tiles along the lines of the cracks were so badly shattered that many of them will have to come out. As a contrast, reference is made to Pl. XLVI, *B*, showing earthquake damage to good brickwork. In the tile wall the same cracks appear, but the tiles are badly shattered for some distance on either side. In addition, in much of the flimsy tile work in the commercial buildings the adhesion of the mortar in the entire partition, if there was any, was destroyed. In the concrete walls at Palo Alto a few cracks appeared here and there as a result of the earthquake; but they were even sharper and narrower than the crack shown in Pl. XLVI, *B*, and there was no shattering effect whatever.

The column coverings in the mail-handling room, described above, were absolutely uninjured, but the circular brick walls around the spiral stairways developed many rather ugly spiral cracks. Such cracks were very conspicuous also in circular smokestacks, where the damaged work was not thrown down entirely.

The floor construction in the post-office was absolutely undamaged by the earthquake. This was one building where "cinder concrete" was made as it should be—of well-burned clinker only. In the court room which burned out a part of the furred ceiling came down, exposing the floor slab above. It may not have received a very severe test; for when work is done as well as it was in this building even a furred ceiling will exhaust the fury of a fairly hot fire. Be that as it may, the floor slab showed no signs of damage whatever, and it was the only case I saw where the heat had evidently reached the floor slab without leaving some degree of damage behind. The fire did not get through the 6-inch hollow-tile walls either, and it took off very few exposed webs. Here again it is probable that the plaster finish was so well done that it prevented the tiles from getting the full effect of the fire. The fire was stopped at the entrance to another court room, where there was a double wooden door, consisting of one door on each side of the partition. Water and wet blankets sufficed to stop the fire at this point, and it is reasonable to suppose that the extra resistance of a second door, even though it was of wood, was a material factor in the result. From a purely technical point of view it is to be regretted that the post-office building was not more seriously involved in the fire, for its fireproofing was of a commercial type—in its best possible form, however. Such a test would have yielded more interesting results than all the rest of San Fran-

cisco combined. It is my personal opinion that the results would have indicated to private owners the availability of a desirable form of fire insurance at moderate cost on which but one premium would have to be paid.

The post-office building was so carefully and intelligently designed and so well executed, and, all things considered, gave so good an account of itself, that it seems a little presumptuous to suggest wherein it could be made better. Yet I believe that if the granite had been solidly backed with good brickwork and even more heavily anchored to the steel frame, if the frame had been more completely and heavily braced, and if all the interior partitions had been of solid brickwork, the structural damage would have been much less; and even the greater weight on the foundations might have been an advantage rather than otherwise. Mr. Roberts estimates the total damage as about $400,000. Of this damage more than one-fourth, much of which was caused by the dynamite, is charged to marble finish and plate glass. The cost of the building was about $2,500,000.

RIALTO BUILDING.

The Rialto Building was a steel-frame structure, with expanded-metal and cinder-concrete slabs, expanded-metal and plaster column covering, and furred expanded-metal ceiling. It had two main wings, in each of which it is said attempts were made to dynamite the building, the explosions causing the collapse of a portion of the interior structural work. A hole in the roof was produced by the same cause. Pl. XLVIII, *B*, a view of the southeast corner of the building, shows a portion of this damage at close range, and is submitted to show the effect of dynamite on a steel-frame building.

The fact that the building was dynamited makes it impossible to draw any useful conclusions as to its fire-resisting qualities; but there seems to have been only a moderately hot fire in this building, and the fireproofing, while seriously damaged, was not a total failure as a result of the fire alone. The north front was badly racked by the earthquake, resulting in many cracks in the walls. The south front of this building was also damaged by the earthquake; the intersecting diagonal cracks in the walls were plainly visible. A considerable amount of face brickwork was thrown off on this front, probably owing to the fact that it was laid without bond.

ST. FRANCIS HOTEL.

The new St. Francis Hotel, which had been occupied but a short time, had a sandstone front and was supported by columns protected with cinder concrete. These columns were entirely undamaged, although a section near the upper end of each column which

had apparently been covered in by a furred beam, or other architectural feature, since destroyed, was entirely devoid of protective covering. A great many people in San Francisco regarded the behavior of these columns as a substantial recommendation of cinder concrete, but the whole building bears evidence of having been subjected to only a moderate heat.

SHREVE BUILDING.

The columns in the first and second stories of the Shreve Building were covered with cinder concrete; those in the upper stories with hollow tiles. All the evidence in this building points to a moderate heat. The plastering on the columns was not seriously damaged, and such plastering never stands an intense heat. The hollow tiles on the columns came off very generally, but it is probable that the heat was more intense in the upper portion of the building than in the lower portion. This theory is supported by the fact that the damage to the masonry adjacent to the windows was most severe in the upper stories.

This building, like the St. Francis Hotel, is cited as an example of the excellent behavior of cinder concrete as a column covering, but in this case also there is every reason to believe that the concrete did not receive a severe test. The only cinder-concrete covering I saw that had evidently received an extreme test was in the basement of the Aronson Building, as described on page 79.

SLOANE BUILDING.

The mercantile structure known as the Sloane Building, at 114 Post street, had cast-iron columns, protected with expanded metal and plaster. The floor slabs were of expanded metal and cinder concrete. The basement of this building was subjected to an extremely fierce heat. At least six or eight of the columns had their covering destroyed, and the columns themselves either buckled or failed to such an extent that a large portion of the framework above was knocked down afterwards as a matter of safety. In the rear of the basement two rows of columns across the entire width of the building had practically all failed in the same way, but the débris was piled around them to such an extent that views could not be obtained.

SPRING VALLEY WATER COMPANY'S BUILDING.

The Spring Valley Water Company's Building, at Post and Geary streets, was used for office purposes in the upper stories and for mercantile purposes in the first and second stories. The southeast corner had totally collapsed (Pl. L, *A*), apparently from the failure of the

basement or first-story columns under the action of the heat. Pl. XLV, *A*, is a view taken in the first story of this building, which had been occupied by the City of Paris Dry Goods Company. This view is submitted as illustrating a typical but rather bad example of the loss of lower webs from hollow-tile floor arches. The column coverings shown in the view had suffered about as little as any others. The coverings of other columns in the same building were practically destroyed, as were also the partitions. The same sort of damage as that shown in Pl. XLV, *A*, was plainly visible in some of the upper stories of this building, especially the second story.

A stairway carried on unprotected cast-iron strings was destroyed by the heat in this building. The same thing occurred in a number of other buildings in San Francisco, even where the stairways had been walled off by hollow-tile partitions or by partitions made of light studs, metal lathing, and plaster. It has generally been considered—in commercial work, at any rate—unnecessary to protect a stairway carried on cast-iron strings, but the San Francisco fire showed that some form of protection is very essential. Where the inclosing partitions did not fail, the stairways were of course not seriously damaged, but as a matter of fact the partitions failed almost everywhere in San Francisco.

UNION FERRY BUILDING.

The Union Ferry Building (Pl. XLVI, *A*) is a large structure—practically of monumental proportions—which forms the terminus of all the ferry lines plying between San Francisco and various other points on the bay. It is built on piles, with heavy stone walls, backed with brickwork. The stone is the grayish-green sandstone elsewhere described. The floor construction consists of steel beams and girders, with stone-concrete slabs reenforced with expanded metal. The lower flanges or girders and beams were not protected. Near the center of the west front a high tower rises to a considerable distance above the building. The fire did not gain entrance, but the building was very seriously racked and damaged by the earthquake. The damage was not at all of a fatal nature, however, and the building was kept in practically continuous operation as a ferry terminus. The tower, which was built with a braced steel frame, inclosed to a height of several stories with a heavy wall composed of sandstone backed with brick, and closed in with wood and sheet metal above the masonry part, was so badly damaged that the masonry walls were being removed at the time of my inspection. To judge by the effects on this tower, the greatest intensity of the earthquake vibration must have been from northwest to southeast. The bracing was badly strained,

and in this case there can be no question that the effect was entirely due to the earthquake. The masonry in the tower was of an admirable quality.

In Pl. XLVI, *B*, is shown a crack in the brick masonry on the inside of the tower, together with a part of a diagonal tie-rod which had been stretched beyond the elastic limit and was hanging with a noticeable sag. It will be noted that the brickwork was well bonded and that the joints were well filled. The mortar was much harder than the bricks, but both were of good quality. It is also evident from this view that there was no general shattering of the entire mass; there was a well-defined crack, but nothing else.

At the northwest corner of the tower, about halfway from the roof of the main building to the top of the masonry walls of the tower, a diagonal tie-rod had been fastened to the wall girder by means of a gusset plate, with eight rivets in it. Seven of these rivets were sheared under the action of the earthquake, leaving the plate hanging by the eighth rivet at the time I saw it (Pl. XLVII, *B*).

One detail of the bracing in the ferry-building tower, of which a satisfactory photograph could not be procured, was as follows: The wall girders at the different floor levels were utilized for the wind struts of the bracing. In the lower part of the tower the diagonal tie-rods were fastened directly to the wind struts. The ends of the wind struts rested between upper and lower seats attached to the columns, and were, as a rule, bolted to each of those seats with nothing but two $\frac{7}{8}$-inch bolts, the idea evidently being that, as the struts resisted compression only, it was not necessary to fasten them to the columns with anything designed to resist any considerable force tending to separate them from the column. The upper seat was evidently designed to take the vertical component of the stress in the diagonal, and the lower seat to take this load in addition to the ordinary load which the wind strut transmitted to it in its capacity as a girder. The bolts fastening the ends of several of the wind struts to their seats had been sheared, and the struts had almost slipped out from between the seats.

In the upper part of the tower a different method was adopted, the diagonal tie-rods being fastened to bent plates that passed around the outside of the columns opposite the ends of the wind struts. No shearing of the bolts or slipping of the struts was noticeable at these points. It is plainly apparent that ordinary assumptions made in designing wind struts will not apply when it is desired that the bracing shall resist earthquakes. There is evidently a tendency for the columns at the ends of a wind strut to buckle outward, and thereby also a tendency to pull the strut out from between its seats. In fastening bracing to resist earthquake shock, therefore, the struts should be fastened to the columns at their ends much more securely than

is ordinarily done. In fact, if the diagonal is to be fastened directly to the wind strut, there should be a connection between the strut and the column capable of taking up the horizontal component of the stress in the diagonals. Knee braces, such as those used in the Call Building, possess a manifest superiority over ordinary bracket seats in construction of this sort. An examination of the condition of the bracing in the ferry-building tower can leave no doubt whatever that the tower was just on the point of total collapse. Conditions were so bad that the superintendent of the contracting firm that was taking the masonry down evidently felt a little uneasy about what would happen when the masonry covering was removed from the portion of the steel work where the bracing was most seriously damaged. He was proceeding with great judgment and caution, however, and no doubt succeeded not only in removing the damaged masonry with safety, but in so tying together the steel work as to avoid all danger of collapse.

A part of the masonry in the east front of the tower was precipitated from its position (Pl. XLVI, *A*) and fell through the skylight and onto the floor of the corridor in the upper story of the main building. This floor consisted of stone concrete, reenforced with expanded metal, and carried by steel beams with spans apparently of 7 or 8 feet. The contractor's superintendent, already mentioned, told me that he thought the amount of masonry so precipitated on this floor amounted to 30 or 40 tons. It punched in the floor one small hole not much larger than a man's fist, but nothing of any size got through. It is doubtful whether any form of floor arch or slab except reenforced concrete and possibly solid brick would have stood this test so successfully. Certainly no hollow-tile floor such as those in ordinary use would have stood it for a moment; the falling mass would have gone on through to the ground.

Along the west front of the ferry building, about halfway up the second-story window piers, most of the stonework had slipped about an inch. Some of the first-story piers were so badly shattered by the earthquake that they had to be boxed in to prevent the loose stone from falling. There were in the floor construction of the tower and of the building proper a few cracks which I thought might be due to the earthquake, although it is possible that they may have been shrinkage cracks. I was not able to get any convincing testimony on this point, but I have seen a good many shrinkage cracks and am of the opinion that most of these cracks were due to the earthquake and not to shrinkage. On the whole, the ferry building stood the shock remarkably well. It would seem to be the part of wisdom, however, to tear the tower down altogether and not to rebuild it.

UNION TRUST COMPANY'S BUILDING.

The ordinary steel-frame Union Trust Building, with terra-cotta fireproofing, came through the earthquake in about the same condition as the average fireproof building in Baltimore after the fire. From the exterior it presented the appearance of having stood the ordeal about as well as any other building in San Francisco that was completely gutted. The damage, however, was probably at least as great as that suffered by such buildings as the Continental Trust in Baltimore. Lower webs were off in many places, and column and girder coverings were damaged to a considerable extent (Pl. L, *B*).

MISCELLANEOUS STRUCTURES.

GENERAL DISCUSSION.

A number of buildings of fire-resistant construction in San Francisco, such as the Mutual Savings Bank, the Hibernia Bank (see Pl. XXXVII, *A*), and several others, have not been specifically mentioned in this report, but they presented nothing of more than ordinary interest. Detailed descriptions have been given of at least one example of everything that was typical, and practically everything described in detail was typical of many other cases of the same general class.

A building at First and Natoma streets had naked cast-iron columns, steel girders, reenforced-concrete beams from girder to girder, and reenforced-concrete slabs from beam to beam. The reenforcement of the concrete beams consisted of plain round rods passing through the webs of the girders and fastened with nuts in the same way as tie-rods. The aggregate of the concrete, in the beams at least, seems to have been of stone. Some of the slabs looked as if some cinders had been used in them, but this appearance may have been due to damage by the fire. At any rate the concrete was very badly damaged, as will be seen in some of the rear bays of the upper floor. Where the deflection was worst there may have been something precipitated upon the floor, but even at other points considerable deflection was apparent, together with serious damage to the concrete. It was evident, from the beams hanging down in the front, that in erecting this building the forms for the beams were filled first and the slabs were put on afterwards, so that there was no adequate bond between the beams and the slabs. The reenforcement of the slabs in this building was a very light twisted-wire mesh, and the only wonder is that it held as well as it did. The remains of a furred wire-lath ceiling were visible, and the failure of this ceiling is typical of what occurred in many other buildings.

It will be noted that there was no reenforced-concrete construction, pure and simple, in San Francisco. The warehouse of the Bekins Van and Storage Company (Pl. XXVII, *A*), in process of construction, had reenforced-concrete columns and floor construction and brick walls. The walls were badly damaged by the earthquake, but the reenforced concrete was absolutely uninjured. This building, however, was unfinished, and the lower portion of it was not subjected to the stresses which would have resulted had it been complete, with all its contents. In that case the energy due to the vibration of the greater superincumbent mass might have produced effects which were not produced in its unfinished condition.

One-half of the circular observatory on Strawberry Hill, in Golden Gate Park (Pl. XXIII, *A*), was thrown down by the earthquake. I did not make a personal examination of it, except from a distance, but was informed that it had been reenforced with heavy iron rods bedded in the masonry. It was reported to me that these rods were broken at the point where the collapsed portion had separated from the part still standing. The general effect of the earthquake on hollow circular structures of all sorts seems to have been a tendency to increase their diameter. Where this tendency was very marked, it naturally caused their collapse.

Practically all the other photographs submitted and not specifically referred to in the foregoing pages were taken with a view of showing earthquake damage. The tower of the church next to the old Mission Dolores was dangerously near being thrown down, and had to be pulled down later, as shown in Pl. XXIII, *B*. Pl. XXXVII, *B*, is a view of a brewery which had been four stories high, with a tower at the corner extending to a considerably greater height than the building. The damage was due to earthquake alone. Pl. XXI, *A*, shows a case of earthquake damage pure and simple. It will be observed that the face bricks were not bonded, and were thrown down in large quantities. None of the brickwork in this building seems to have been of a very good quality.

An old-fashioned brick building of ordinary construction near Fort Mason appeared to have survived the earthquake absolutely undamaged. This example indicates the variation in the intensity of the earthquake within relatively short distances.

Pl. XXXIII, *A*, shows a building, known as the Butler Building, which was partially completed at the time of the earthquake. When I first saw it the side wall, which appears in the illustration as nearly torn down, was standing at about the same height as the front wall (shown at the right side of the picture). This side wall had a few earthquake cracks in it which were plainly visible, but it was a matter of surprise to see, a few days later, that the wall had been practically torn down; for if this wall was damaged sufficiently to

justify its destruction, a great many walls of other steel-frame buildings ought to have come down also. This building was of the ordinary steel-frame type, without any bracing. The walls were very light, and on the principal fronts they were pretty well shaken to pieces. A superficial examination indicated that they were much more seriously damaged than the side wall which had been torn down. This building appears in the background of the view of the Dewey monument (Pl. XXX, *A*). At the time this view was taken a considerable amount of the masonry in the front wali had been removed, but there was still a great deal which, in my judgment, was too badly damaged to be safely left.

Pl. LV is a panorama taken from Pine and Powell streets. The building on the left side of the street at the left is the Merchants' Exchange. To the right, just behind the high ground and trees, is the Mills Building, and farther to the right is the Union Trust Building. The other buildings will probably be recognized by persons who are more or less familiar with the city; the names of the chief ones are given on the plate. It will be observed that this panorama covers an arc of nearly 180°. The Twin Peaks appear some distance to the right of the city hall.

ORDINARY BUILDINGS AND RESIDENCES.

The effect of the earthquake on miscellaneous buildings of the cheaper class was more or less interesting. There were a number of brick dwellings in San Francisco faced with arch bricks laid in Flemish bond. These bricks, of course, are considerably harder and stronger than ordinary red bricks. Though they make a very rough wall, it is interesting and attractive, like the old colonial brickwork in the East. Apparently these houses were very strong. Whether it was good luck in all cases, or whether this brickwork really was much superior to the average brickwork used in San Francisco, I saw not a single example of earthquake damage to any house built in this way. I noticed eight or ten of these dwellings, and not one of them was damaged. The same fact had been noticed by the enlisted man who accompanied me as a photographer. He apparently had seen a greater number of buildings of this kind of brickwork than I had, and he stated that not one of them seemed to have suffered any injury, although, in many cases, their neighbors had been seriously damaged.

A considerable number of frame buildings had practically collapsed under the earthquake; some of them were thrown bodily from their foundations. Plaster was generally shaken loose from wooden lathing, but, so far as I saw, none that was applied to good metallic lathing, such as heavy wire lath or expanded metal, had been shaken down.

As a result of my observations, I am inclined to think that a building of the following type would be very desirable for residential purposes in an earthquake country:

The frame should be of timber, rather heavy and thoroughly braced, with all the vertical members continuous from bottom to top, or else thoroughly spliced. The horizontal members should be made as nearly continuous as possible—preferably by full splices. Horizontal and vertical members should also be fastened together as rigidly as possible, diagonal braces being used wherever conditions will permit. The frame should be covered on the outside with expanded metal and this metal plastered on both sides, a good deal of cement being used in the plaster. The exterior can be finished in stucco or pebble dash, as desired. The interior of the frame should be covered with expanded-metal lathing and the ordinary interior plaster-finish put on. The ceilings also should be finished with expanded metal and plaster. In my judgment, a building of this sort could be put up for very little more than the cost of an ordinary frame dwelling, and would not only come through an earthquake much better, but would be very much more difficult to set on fire and would burn much more slowly after it was on fire.

CHIMNEYS.

Chimneys seemed to be shaken down by the earthquake everywhere; even where there was no other damage this result was almost universal. The chimneys, as a rule, were built of bricks laid in lime mortar, and generally broke off at the point where they came through the roof. Reenforced-concrete chimneys with a terra-cotta lining would be very little more expensive than the kind that were ordinarily used in San Francisco, and would have suffered very much less damage. If any chimney projects a considerable distance above the roof, it would be advisable to brace it near its upper end to the roof in some way, so that it would not be free to vibrate. It seems probable that this plan might have saved some of the chimneys that failed. Appearances seemed also to warrant the conclusion that in the vibration some chimneys were brought up short against the roof framing and thus caused to break off at this point. If there had been a little more room for relative vibration between the chimney and the framing, it seems possible that some of these chimneys would not have fallen. The best way to prevent such damage is to build the chimneys of reenforced concrete or of some other material that has both rigidity and great tensile strength. Such chimneys would not ordinarily break off, even though they jostled against the roof timbers.

BRICK SMOKESTACKS.

There were a great many brick smokestacks in San Francisco, nearly all of which suffered more or less damage. For some reason circular stacks seemed to suffer more than square ones, but the number of square stacks in evidence was not sufficient to justify general conclusions.

The views of brick stacks speak for themselves to a great extent. The stack of the Valencia street power station (Pl. LIII, *A*) was of some interest because of its peculiar cross section—an eight-pointed star. At the vertices of two diametrically opposite reentrant angles the stack was split practically from top to bottom. The ruins of a circular stack, situated near San Jose, are shown in Pl. XIII, *A*.

CONDITIONS OUTSIDE OF SAN FRANCISCO.

OAKLAND.

I made one trip to Oakland and went through the greater part of the town. A good many chimneys had been shaken down and the front walls of a number of ordinary brick buildings had been precipitated into the street. Several steel-frame buildings faced with sandstone were badly racked, and in places some of the stone had been shaken into the street. Some of the steel-frame buildings showed the same kind of damage as the Monadnock and new Chronicle buildings in San Francisco. The damage in Oakland in general was not different in type from that in San Francisco, but it was much less extensive, and individual cases were, as a rule, much less marked.

PALO ALTO.

I visited Palo Alto, and through the courtesy of President Jordan, of the Leland Stanford Junior University, was enabled to make a satisfactory examination of the damaged buildings at the university. These buildings represented in a general way three different types. Among them were some old buildings faced with yellow sandstone, which had been built in the early days by hired labor, under the supervision of Governor Stanford himself. All the sandstone used at the university was of a light yellow-buff color, rather soft, and apparently not very strong. In these older buildings, however, the cut stone had good wide beds, was carefully laid, was well bonded to the backing, and was solidly backed up with brickwork. These buildings were damaged seriously, but by no means beyond repair.

In addition to these older buildings there were some newer ones of the same general design, but the sandstone facing was thinner and the beds not so well cut nor so wide. The backing was not so good.

Much of it consisted of rubble made of very small pieces of stone, apparently gathered up where stonecutters had been working. Many of these spalls were not larger than a man's fist, and in places 4 or 5 square feet of the wall was entirely backed up with this material. The bonding of the stone facing to the backing seemed to be less thorough in the new buildings than in the old. In short, the newer buildings conformed rather to the modern commercial standard of building construction; the old ones approached the monumental. The newer buildings suffered materially more than the old. They were not, however, of a type that would indicate culpable negligence or incapacity on the part of anyone connected with their design and erection, although they were distinctly inferior in type to the older buildings. The mortar used was not by any means poor. It seems to have been lime mortar gaged with cement. I tried it at a number of points where the buildings had suffered very severely, and it was distinctly better than the average mortar found in ordinary commercial work, although not as good as straight cement mortar would have been.

The buildings of the third class at Stanford University were built of concrete. The girls' dormitory had concrete walls and timber interior construction, and in the central portion of the Leland Stanford Junior Museum, the oldest part of the building, the walls and interior construction were of reenforced concrete. There were two wings, built of brickwork, with reenforced-concrete floor construction. It is reasonable to suppose that the intensity of the force applied to this building by the earthquake was nearly uniform over the entire structure. The two brick wings were practically shaken down, suffering, I should judge, considerably more than 50 per cent damage. The reenforced-concrete central portion, viewed from the exterior, seemed absolutely undamaged. In the interior a few cracks had opened up, but they were not of serious consequence. I should judge that a thousand dollars would easily cover all the repairs to this part of the building. Its valuable contents were, to a large extent, thrown to the floors and smashed, involving a considerable loss; but the structure itself suffered almost no injury. The only damage to the girls' dormitory was caused by a chimney that toppled over and crashed down through the roof, doing some damage on the inside. By good luck, no one was hurt in this building. The concrete wall showed one or two cracks, which, however, were said to be shrinkage cracks that had appeared soon after the building was finished. The earthquake apparently had caused no visible damage of any sort in the exterior walls.

It was noticed that those buildings which had completely trussed roofs suffered much less than those in which the walls had to take

the thrust of the rafters. This result was naturally to be expected, and indicates that in earthquake countries walls should not be subjected to the thrust of the rafters at all. The damage at the university also indicated clearly the necessity of thoroughly tying all the walls to the roof construction, gable walls as well as others. The university post-office building was said to be of reenforced concrete and undamaged. Very good illustrations of the damage at Stanford University can be seen in the Engineering News for May 10, 1906, and in the Engineering Record for May 12, 1906. (See also Pls. XIV, *A*; XV; XVI; XVII, *B*; XVIII.) A concrete-block building in the town of Palo Alto was totally demolished.

OTHER TOWNS.

Concrete-block buildings elsewhere were also reported as totally destroyed. The various structures of the Southern Pacific Railroad along the coast division had suffered more or less damage. One or two stations faced with a sandstone similar to that used at the Leland Stanford Junior University, and built in the ordinary style, had been very seriously damaged. One station, which seemed to have been built a little more carefully and with larger stones than the rest, was in very much better condition than most of them. The city hall at Redwood had a central circular tower, with a dome supported on steel work, much as in the city hall at San Francisco (Pl. XXXI), though on a smaller scale, and suffered almost exactly the same kind and degree of damage.

FORTIFICATIONS.

I visited the old brick fort at the Presidio and also most of the batteries along the face of the cliff. There were a few cracks in the old brick fort, but nothing to indicate that they might not have been due to settling as well as to earthquake. An inspection of the new emplacements from the exterior showed no visible signs of damage whatever. As reports on these matters are made by officers especially in charge of the work, I did not attempt to make a detailed inspection of the fortifications.

RESERVOIRS, PIPE LINES, AND OTHER STRUCTURES ALONG THE FAULT LINE.

The following details were derived from a perusal of the report by Professors Marx and Wing, already mentioned (p. 63).

The Spring Valley Water Company had among its reservoirs two known as Crystal Springs Lake and San Andreas Lake. The line of the fault that caused the earthquake is said to run directly through both of these reservoirs. Crystal Springs Lake has a large and high concrete dam; it is also subdivided by an old earth dam that was

formerly the main dam, when the reservoir was smaller than it is now. The concrete dam, which was parallel to the fault and of course very near to it, was absolutely uninjured (Pl. XI, *B*); the earth dam, which lay across the fault approximately at right angles, showed definite signs of disturbance and lateral displacement. Longitudinal and transverse cracks appeared on top of the earth dam, and some of the former were reported to have extended to a depth of at least 3 or 4 feet. The transverse cracks were said to be less well defined and to indicate rather a general disturbance on each side of the fault line, about one-fourth of a mile away, and was absolutely to which it was damaged could not be ascertained.

San Andreas Lake is retained by a high earth dam. The fault ran under the east end of this dam and produced considerable disturbance over a strip about 150 feet wide, though the dam was not seriously injured. A concrete culvert inlet was connected with this dam, and one of the worst transverse cracks noted ran diagonally over the culvert, but the culvert itself was uninjured. Besides the high concrete dam of Crystal Springs Lake, the water company had another smaller concrete dam at Searsville. This dam also was parallel to the fault line, about one-fourth of a mile away, and was absolutely uninjured.

The Spring Valley Water Company had three main conduits running into San Francisco. One of these, known as the Pilarcitos conduit, consisted largely of 22-inch and 30-inch riveted pipe and 24-inch cast-iron pipe; some feeders were built of wooden flume. The conduit crossed and recrossed the line of the fault, and was so badly wrecked that the company has decided to abandon it—no doubt a wise decision, because the location along the line of the fault was a very bad one. Wherever the conduit crossed the fault line it was destroyed. In some places there was a longitudinal displacement of as much as 84 inches, which either telescoped the pipe or pulled it apart, as the case might be. (Views of these effects are given in Pl. IX.) It made no difference whether the conduit was in firm ground, or in soft ground, or carried on a trestle over marshy ground; the result was the same wherever it crossed the fault. In many places where the conduit was carried on trestlework the timber showed considerable decay. Whether sound timber structures would have withstood the shock seems open to question. (See also Pl. X, *A*.)

Within the city proper the reservoir known as Lake Honda was damaged by the cracking of its concrete lining. It is reported that this cracking was due to the displacement of a retaining wall by a sliding bank set in motion by the earthquake.

The distributing mains of the Spring Valley Water Company, wherever they passed through soft or made ground, suffered in the

same way as the conduits and pipes which crossed the fault line. (See the maps, Pls. LVI and LVII.) Some subaqueous pipe lines crossing the bay seem not to have been injured.

Two interesting earth dams are those at the San Jose Water Company's Saratoga reservoir, which lies in a saddle in the mountains and is retained by an earth dam at either end. The fault runs directly through the reservoir, crossing both dams approximately at right angles. It was reported that near the east end of the north dam transverse cracks were formed, which extended through the body of the dam. There was also a longitudinal crack on top and some settling of the upstream half of the dam. The reservoir seems to have been full at the time of the earthquake, but no evidence was found that any water had escaped through this dam. At the south end of the reservoir the fault line intersected not only the dam but the 10-inch outlet pipe, which was broken by the earthquake. Considerable damage seems to have been done to the dam by the water escaping through this broken outlet pipe. Whether the dam itself would have been seriously injured by the earthquake but for this pipe can not probably be determined.

Professors Marx and Wing also noted in the vicinity of the fault a number of monolithic concrete bridges, all of which were uninjured; none of them, however, absolutely crossed the fault line. (Cf. Pl. XI, *A*.) These observers also report that a small concrete reservoir, built partly in embankment and partly in excavation, was wrecked by the earthquake, and seem to think that such structures would better be built in excavation. They found that some high timber frames carrying water tanks, as well as similar structures supporting steel standpipes, were intact. A steel water tower at Santa Clara was wrecked. The engineer who designed this tower gives an explanation of its failure, however, in the Engineering News for May 10, 1906. Very probably his explanation is correct, and if so, there is no reason why steel towers should not be used. Doctor Jordan told me of one tower that he saw which had collapsed as a result of the earthquake, and in which the nuts on the upper ends of the anchor rods stripped the threads so as to allow the tower as a whole to be thrown over.

GENERAL CONCLUSIONS.

THE REBUILDING OF SAN FRANCISCO.

Unless future earthquakes are very much more severe than any that have occurred, there is no reason why the rebuilding of San Francisco should not be a successful commercial enterprise. It seems highly improbable that there will ever be earthquakes more severe than that of April 18, 1906. There is no doubt that the city can be rebuilt

so that, although it will suffer damage from future earthquakes, this damage will not be at all fatal, and the city will not burn up as a result of it.

DISTRIBUTION SYSTEMS FOR WATERWORKS.

In a city subjected to earthquakes it seems practically impossible to suggest any method of construction which will make the mains and distributing pipes at all times perfectly secure. In my judgment the only remedy is to have within the city itself a large storage capacity, distributed among various reservoirs, and to have a more than ordinarily complete gridiron of mains with gate valves to cut out any main at every intersection. Further, the mains should be larger than would ordinarily be required, so that if a portion of the gridiron were shattered it could be cut out, but the water could be brought in undiminished quantities to the perimeter of the shattered area from all undamaged parts of the gridiron; that is, the mains should be so large that, although the water would have farther to travel in this case, there would be an adequate supply for fighting fire, if necessary, in the area where the mains were shattered.

It would seem that in a city like San Francisco a special system of high-pressure salt-water mains, supplied from a pumping station, would be the best solution of the fire-fighting problem so far as the congested district is concerned. This plan has been recommended by the National Board of Fire Underwriters, and it is probably the wisest one under the circumstances. The pumping station should, of course, be protected from earthquake damage in every possible way. Perhaps it should be a floating station. The salt-water mains should be so laid out and so interconnected that nothing short of general destruction of the entire system could wholly shut off the water from any considerable area.

In a city like San Francisco, where there is practically no damage from freezing, it would seem worth while to run the mains exposed everywhere, so that breaks could be located almost immediately. As these breaks would ordinarily occur only in scattered localities, and would not be very great in extent themselves, it ought to be possible to repair them in time to prevent any general destruction of the city by fire. Running the mains exposed would, of course, introduce difficult problems at street crossings, but there is little doubt that such problems could be solved successfully if they were seriously studied. All this means greatly increased expense in the distribution system, but in a situation such as that of San Francisco it seems to be required.

The earthquake effects at San Francisco also indicate clearly that a special study should be made of the problem of promptness in emergency repairs to the conduits and mains. It seems certain that,

in the immediate vicinity of existing faults and near areas including any considerable amount of made ground, both conduits and mains may be expected to suffer serious damage. At one point on Van Ness avenue (see B, Pl. LVI), where I happened to see the mains uncovered, a heavy water pipe, apparently about 20 inches in diameter, had been broken into pieces not more than 2 feet long. The total length of the break, however, was not more than 40 or 50 feet, so far as I could judge from what I saw uncovered. It would seem that this main might have been spliced in a few hours had there been some means of rapidly plugging the broken ends on either side of the break and making a number of taps in the undamaged parts with parallel lengths of fire hose of large size. With gate valves at short intervals it ought to be possible to cut out any damaged portion of the system by connecting through with fire hose in such a way as to maintain at least a partial supply of water for fire-fighting purposes. Some similar plan on a larger scale might be devised for repairing conduits.

It would also seem desirable, wherever an important conduit or main crosses filled ground or material soft enough to suffer consolidation as a result of thorough shaking, to carry the main on piles or other foundations reaching to firm material below. Wherever there was filled ground the vibration due to the earthquake seemed to have much the same effect as would be produced in a vessel that had been loosely filled with sand and then subjected to vibration; as is well known, the sand, under such circumstances, will suffer consolidation to a very appreciable extent, which naturally lowers its surface by an amount corresponding in a general way to the intensity of the vibration. Where a large area and volume of made ground is subjected to similar vibration, subsidence occurs, and not only are buildings on the surface thrown down and destroyed, but water mains, sewers, etc., running through the filled material are subjected to a deflection which necessarily shatters them.

SEWERS.

The effect of the earthquake on sewers seemed to be practically the same as on conduits and water mains, except as varied by difference of material, where such difference existed. The necessity for firm foundations for sewers running through made ground is clearly indicated. The need of rapid repairs to the sewers is not quite so great as in the case of the fire mains, because a city can get along with inadequate sewerage facilities, if necessary. It would seem desirable, however, that all important sewers passing through made ground should be constructed of the heaviest iron or steel pipes, and be provided with an adequate foundation. Of course, sewers are not

under pressure, and therefore can not be repaired with fire hose, as suggested for water mains. There seemed to be some fear in San Francisco that the breaking of the sewers and the water mains would cause the water to be contaminated by the sewage; but evidently if means were devised to maintain a good pressure in the water pipes this pressure in itself would protect a leaky main from such contamination.

FIRE-RESISTING FEATURES OF BUILDINGS IN "CONGESTED DISTRICTS."

FIREPROOFING.

The Baltimore and San Francisco fires, as well as many other fires and fire tests, have proved conclusively that commercial methods of fireproofing are inadequate to stand any severe test. In most buildings the steel work is fairly well protected, but the number of failures is sufficiently great to show that the factor of safety against fire is not by any means what it should be.

For the protective covering itself to suffer complete destruction, or almost complete destruction, in any one fire is in itself a failure, because under such circumstances the steel work is very near destruction and the margin of safety is altogether too small. It is more than probable—almost certain, in fact—that a detailed investigation of all the buildings in San Francisco would reveal many "protected" columns, not indicated in this report, that buckled as a result of the failure of the covering. In my judgment, columns should either be covered with 4 inches of brickwork, laid in Portland-cement mortar, and have all of the interior space filled with concrete, or else they should be inclosed in an expanded-metal jacket and the entire interior filled with concrete, so that the minimum thickness of the concrete would not be less than 4 inches. Exposed flanges of girders and beams should be protected by the equivalent of 1½ to 2½ inches of solid porous terra cotta, according to circumstances. If concrete is to be used, this thickness should be increased by about half an inch. The protection for lower flanges should always be inclosed in a basket of expanded metal or heavy wire lath, securely anchored into the side protection of the webs. The San Francisco experience showed that, even in a hot fire, such metal-mesh basket work will largely retain its tensile strength, and thus hold in position the fireproof covering inside even though the latter should be shattered by expansion stresses or otherwise. The webs of the girders should be covered by 4 inches of brickwork or concrete, built up on the lower flanges. Girders should be completely covered from bottom to top before the floor systems are put in, so that the collapse of the latter will not expose the girder. Floor beams should have heavy, solid protecting

skew backs, not less than 1½ inches thick, or be covered with at least 2 inches of concrete. In an important work the protection of the lower flanges of the floor beams should also be incased in expanded metal or wire lath. The furred ceilings so much used in San Francisco are a valuable addition to the fire-resisting qualities of floor construction, and if the furring rods were more firmly secured the total loss here, as a rule, would be measured by the value of the plaster alone.

Hollow-tile partitions should not be less than 6 inches thick. The tiles should have webs at least 1 inch thick, and all interior angles should be well filleted. The tiles themselves should be carefully laid in Portland-cement mortar, with all joints absolutely filled. Timber studs running to the top of the partition, to frame a door or window opening, should be absolutely prohibited. The webs of floor tiles should not be less than an inch thick, and their interior angles also should be well filleted.

The results at Baltimore and San Francisco did not, by any means, indicate that either hollow tile or concrete is altogether a failure or altogether a success. Both fires indicated very clearly that commercial methods of applying both materials are inadequate, but also that successful results can be attained with both materials.

A conflagration never yields reliable comparative results, but judging from such comparative results as are available, I think that there is no question that the best fire-resisting material available at the present time is the right kind of burned clay—that is, a good, tough, refractory clay, almost as refractory as fire clay, made into proper shapes and properly burned. Some commercial hollow-tile work is made of good material, but, as a rule, that is the only good thing that can be said about it. There can be no question that good clinker concrete, made of well-burned clinker, Portland cement, and sand, is a very efficient fire-resisting material. It is better than anything except the better types of burned-clay products; but the cinder concrete commercially applied is, on the whole, no better than the flimsy hollow-tile work with which it competes; in fact, it is not certain that it may not be worse. The only way to determine this point would be to go through all the floor construction in a place like San Francisco and make tests of the load-carrying capacity, etc., after a fire. It is very doubtful, of course, whether such tests will be made.

If a hollow-tile floor, for instance, loses its lower webs, the damage is very apparent, yet most of such floors remain true and capable of carrying considerable loads. A cinder-concrete floor which is even more seriously damaged is very likely to remain true, for the reason that the fire which damaged it also removed its superimposed load before the damage was fully accomplished. A hollow tile which comes through a fire without losing any of its webs is as good as it

was before; whereas concrete of any kind which has come through a fire in which the temperature has exceeded 700° or 800° F. is inevitably damaged in all cases, owing to the dehydration of the cement, although it may appear uninjured to the casual observer. This property of concrete, of maintaining a good face in spite of real and serious damage, is likely to lead the layman into dangerous conclusions, and consequently into equally dangerous practice. It would seem that wherever reenforced-concrete floor construction is used a furred ceiling below it should be absolutely required.

The furred ceilings ordinarily used are too light; the furring rods are not quite heavy enough and they are not adequately secured to the floor construction above. If they were made a little heavier, and were more firmly secured, it is probable that, as a rule, no loss would occur except that of the plaster. Even if the furred ceiling comes down bodily, this failure is not apt to occur until so late a stage in the fire that the floor construction above will be practically undamaged, because there will not be enough left of the fire to raise the temperature of the concrete to the point where dehydration of the cement will begin. The presence of a furred ceiling, however, no matter how good, should never be accepted as an excuse for omitting the protection of the lower flanges of the floor beams and girders. A hollow-tile floor that would be fully equivalent to a reenforced-concrete floor, with a furred ceiling, could be made by using tiles in which the minimum thickness of the webs is 1 inch, and of which the material itself is tough, refractory clay, made porous by the addition of sawdust; such tiles should, however, be burned to a point where the clay itself is just short of vitrification. All the interior angles, where the webs of the tiles join each other, should be rounded to a radius of at least 1 inch or 1½ inches. If necessary to secure proper burning, a small hole three-eighths to five-eighths of an inch in diameter might be allowed through the mass of clay at the intersection of the webs.

Tests recently made of a pattern of tile used at the War College indicate that floor tiles subjected to a fire test will stand better if there is but one interior hole through the tiles, all the material which would otherwise be used in the interior webs being concentrated in the outer webs, and the opening in the tile being of circular or elliptical shape, depending on the height and width of the tile. For floor arches between steel beams such a tile as this one would have to be used on the end-construction plan. A specially heavy skew back should be designed to go with it, or else the end tiles should be cut to fit the profiles of the beam. The tiles themselves being so heavy, the latter method of obtaining a skew back would probably make the arch more than strong enough to carry its load, and where carefully done might afford adequate fire protection to the beams,

although for that purpose a specially designed extra heavy side-construction skew back would be better, and should on the whole be recommended even in connection with the heavy end-construction arches described. It is probable that either a good concrete floor with the right kind of ceiling below it, or a heavy tile floor such as that herein described, would come through almost any fire with no damage except the loss of the ceiling plaster. These two types may therefore be taken as equivalent in efficiency; they will probably be about equal, also, in first cost.

It should be added that attic floors and roofs should be as carefully designed to resist fire as any other part of a building. This is a thing that has rarely been done, and the experience of both Baltimore and San Francisco shows that it is absolutely necessary.

PROTECTION OF OPENINGS.

While there is no doubt that commercial standards of fireproofing are dangerously inadequate, the greatest trouble of all is the fact that so little attention is paid to protecting the exterior openings in a building. Even a very inefficient type of fire shutter would probably have saved some of the buildings in San Francisco, which were, as a matter of fact, burned out. A light metal shutter combined with a window sprinkler would probably resist a rather fierce fire for a long time. Although the failure of the water supply in San Francisco might be urged as one reason why a window sprinkler would have been of no avail, it is a fact that water can be obtained by driving wells into the sand which underlies the business portion of San Francisco almost everywhere. Under these circumstances, if the fireproof buildings had been fitted with metal shutters, even no better than those in the windows of the hall of records, and if each window had been provided with a sprinkler and the building itself with its own well and fire pump, it is probable that the fire could have been kept out of a large number of the buildings. The protection of external openings is by all odds the most important constructive problem involved in the efforts to make cities proof against conflagration, and it seems probable that at the present time adequate protection of windows and doors is available at a reasonable cost. In my judgment, windows protected in the following way, even without sprinklers, might keep out the fire, though the buildings were shut up and abandoned.

1. The outer opening should be protected with some form of rolling steel shutter or, preferably, with a shutter composed of sheets of steel sliding in very deep rebates in the walls. The sheets of steel should be anchored in these rebates by means of angle irons or rivets driven so as to interlock with a bead to be placed in position after

the sheet of steel is itself in position. By providing a pocket in the masonry just above the window head and making these shutters in three or four parts, overlapping and interlocking at the overlap, the whole shutter could be slid up into the wall practically out of sight. This arrangement would necessitate window openings slightly lower than those used in many commercial buildings, but the loss of light would not be very serious. The metal shutters when closed should overlap the window opening in all directions by at least 6 inches. This overlapping could be accomplished at the sill without making a pocket to catch water and dust, by forming a step in the sill itself.

2. The windows should be made entirely of wire glass, with sheet metal or metal-covered sash, hung in metal or metal-covered frames. Clear wire glass can be used if desired.

3. On the inside of the window there should be a sliding shutter, either of wood covered with sheet metal or of sheet metal such as that described for the outside. If the outer wall is furred, a pocket could be made between the furring and the wall, so that the inside shutters could be slid sidewise.

It is probable that under a fairly bad exposure to fire the outer shutters here described would be so damaged that they would have to be removed. In a conflagration they would probably be warped to such an extent as to let the heat in, and possibly to soften the wire glass and damage the windows themselves, so that they also might have to be renewed—at least so far as the sash were concerned. But it is very doubtful if any conflagration would ever get through the sash, much less through the inside shutters. Any damage to the window protection, however, would be a very small matter compared with the total destruction of the contents of the building and a damage of 65 to 80 per cent to the building itself.

Window protection of the kind just described could be so designed that it would not be objectionable even on the principal fronts of buildings. The San Francisco and Baltimore fires have demonstrated that all the exterior openings of even fireproof buildings need protection. It would seem that the time has arrived when building ordinances should require it.

If to the triple window protection described above a window sprinkler with adequate water supply is added, a defense which will probably not only be adequate for its purpose, but which will suffer small damage itself, will be provided. This system of protection, while it has never been applied, can be applied at a cost which is not prohibitive, especially if unnecessary and expensive finish is omitted.

Practically all the fireproof buildings in San Francisco were unshuttered. Many nonfireproof buildings were partially shuttered, but no building, except that of the Pacific States Telephone and Tele-

graph Company on Bush street, was completely shuttered. Although every opening in this building was protected, it is not certain that the fire did not find its way into the building through some of them in spite of the protection. The protection of individual openings apparently was not quite heavy enough.[a]

The view of the main front of this building (Pl. XLI, *A*) shows plainly that it was not severely attacked by the flames, yet it probably would have resisted such an attack a good deal better than the façades of many other buildings. The exterior architraves of most of the windows are of solid molded brickwork, and the amount of hollow terra cotta in the exterior front is reduced to a minimum, so that this building would probably not have suffered quite as much as the average, even if the fire test from the outside had been fully as severe.

FIREPROOF VAULTS.

It would seem that the question of so-called fireproof vaults in commercial office buildings should also receive some attention. The failure of such vaults in San Francisco is absolutely inexcusable. The fact that they were so flimsy was not due to any lack of available knowledge as to how a fireproof vault should be built; the only motive that can be imagined for the erection of such vaults is parsimonious and criminal economy. (See Pl. LII.)

CONSTRUCTIONS AND MATERIALS RECOMMENDED FOR EARTHQUAKE LOCALITIES.

For every tall building the best type of construction is undoubtedly a steel frame, but it should be thoroughly braced in much the same way as in the Call Building, where the steel bracing undoubt-

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[a] Since the above was written the following information has been received from California, through the courtesy and cooperation of Capt. M. L. Walker and Capt. William Kelly, both of the Corps of Engineers:

The rolling shutters on the Bush street building of the Pacific States Telephone and Telegraph Company were made of interlocking slats crimped out of heavy sheet iron, the shutter as a whole sliding at the sides of the opening in heavy iron guides. Captain Kelly thinks they were made of No. 22 iron. I do not believe, personally, that these shutters withstood the direct impact of fierce flame for a great length of time; they would have warped and pulled apart so as to let the flame in. The view of the Bush street front of this building (shown in Pl. XLI, *A*) would indicate that there was no direct attack by the flame from the outside, and there is every reason to believe that the plate glass on the inside stood long enough to prevent the shutters from receiving any serious attack from the flames of the interior fire. It is probable, however, that these shutters are fully as efficient as the rolling shutters made by other manufacturers out of continuous sheets of corrugated iron riveted together along the edges. The continuous sheets have to be of rather light metal, in order to make them practicable; and when subjected to any great amount of heat they invariably pull apart along the lines of rivet holes—a weakness which was clearly illustrated in the Baltimore fire. There would seem to be no doubt, however, that rolling shutters of either type used on the outer windows of a building would effectually prevent ignition from radiant heat due to a fire in a neighboring building. They would also, of course, resist for a time the actual impact of flame, but I am personally of the opinion that they could not resist this form of attack for very long.

edly saved the masonry. In such buildings as the new Chronicle and the Monadnock the effect of the vibration was really resisted by the masonry, which was much shattered. Some of it was precipitated into the street from the new Chronicle Building, the Rialto Building, and others. It is not at all certain that the steel frames of these buildings have not also been seriously damaged by the earthquake. Naked steel frames of the same type came through without serious damage, but they did not suffer the additional stresses due to the vibration of a great load of masonry, floor construction, and contents in the upper stories, as did the finished buildings. It is not right to run the risk of precipitating the masonry into the street on the heads of passers-by, as would have happened at the unbraced steel-frame buildings had the earthquake occurred at a later hour in the day. Besides, if the strength of the building is dependent on the masonry, which is seriously shattered by the stresses that it is expected to resist, the factor of safety against general collapse is manifestly too small. The steel-frame construction should therefore be thoroughly braced. In my judgment, to obtain the best results it should also be inclosed with walls of reenforced concrete, in which case it would be almost impossible to throw the walls off. The proper artistic treatment of this material in a place like San Francisco would seem to be a very important problem for the architects. The great utility of reenforced concrete in earthquake shocks can not be denied. Where steel-frame buildings are to be finished with ordinary masonry walls, however, complete bonding of all face bricks with full header courses should be absolutely required. No other form of bond is adequate. Nothing but Portland-cement mortar should be allowed in any part of the structure. The masonry should be tied to the steel frame in the very best possible way, and much more securely than is ordinarily the case.

For buildings of moderate height, say up to 125 feet as an extreme limit, reenforced concrete alone can undoubtedly be so designed as to give very good results when subjected to either earthquake or fire. But the bracing of a reenforced-concrete building of any height to resist earthquake is a matter for serious study. The problem can be solved, but it has not been solved yet.

Any building of considerable height, in an earthquake country, should have as little mass in the superstructure as possible, consistent with other necessary qualities. But this limiting of mass does not mean that the flimsy floors and partitions heretofore in use should be continued. In fact, to make the buildings proof against both earthquake and fire it is probable that they will have to be at least as heavy as they have been, but changes in distribution of the mass could advantageously be made.

For the ordinary commercial building, where brick walls and wooden joists would ordinarily be used, I am of the opinion that the use of reenforced concrete would be the safest and most practicable solution in a place like San Francisco. Where reenforced concrete is used throughout, whether the building is very tall or not, great care should be taken with the design and execution of the connections between the columns and the members of the floor system. There should be heavy knee braces for the connection of all girders and beams, and, wherever possible, portal bracing in the shape of reenforced-concrete arches should be introduced. Of course the amount of this work that needs to be done depends on the circumstances in each individual case, such as the height of the building, its horizontal area, the kind of material, the dead weight in the upper stories, etc.

The opposition of the bricklayers' union and similar organizations has hitherto prevented the use of reenforced concrete in San Francisco for all parts of buildings. This action of the labor unions has probably cost the city a good deal, and, should it be continued, will cost a great deal more in the future.

From the effect on the fortifications, and on monolithic and massive concrete structures elsewhere, as indicated by the details taken from the report of Professors Marx and Wing, it seems justifiable to conclude that a solid monolithic concrete structure of any sort is secure against serious damage in any earthquake country, unless it should happen to lie across the line of the slip; in that case the damage might be fatal, or it might not, depending altogether on the amount of the slip and the intensity of the forces that accompanied it.

It would seem that earth dams of ample size and with good foundations are also secure against fatal damage unless they are traversed by the slip. Even in the latter case the damage would appear to be not always fatal; that it would never be fatal, however, would be a rash assertion to make. It is unsafe to say that any sort of structure could be built so that geologic faulting could occur immediately underneath it without doing serious damage. As a matter of fact, however, most structures in an earthquake country would not lie on the line of a fault, and it seems quite certain that in such cases well-constructed earth dams and solid monolithic masses of concrete, whether large or small, would escape serious injury.

THE MINIMIZING OF FIRE LOSSES.

A study of the results of the Baltimore and San Francisco fires, especially in connection with the statements of adjusted losses at Baltimore, readily discloses the following facts:

In the first place, the contents of the fireproof buildings were a total loss. In many buildings the contents might probably be worth

more than the structure itself, especially if any attempt is made to fix the value of records and papers that can not be duplicated. In the second place, the buildings themselves suffered a damage exceeding 65 per cent, and in San Francisco probably amounting to almost 80 per cent. A study of the items entering into this damage discloses the fact that a very large proportion of it is due to the loss of the architectural finish, such as face brickwork, ornamental terra cotta, and stonework on the exterior; marble dadoes, columns, and other finish on the interior; wooden door and window frames, wooden doors and windows, ornamental grillwork, etc. If the fireproof-building problem is to be solved in such a manner that conflagrations will not cause serious losses, it would seem that radical revision of the method of finish is necessary. As the finish must practically be a total loss anyway, it should be so devised that it can be replaced at small expense. This requirement, however, makes it impossible to adopt a material for the construction which, as the architects say, finishes itself—because, if the exposed surface is destroyed, the material becomes a total loss. It would seem that for the exterior of the structure, walls well built of good, common brick, laid in Portland-cement mortar, or else of reenforced concrete, could be finished on the outside with stucco, pebble dash, or some similar material. The opportunity for the effective use of colors here would be very great. If the buildings were exposed to a fire, the exterior finish would probably be a total loss, but its value in dollars and cents is small. The fire might even strip it off and cause serious spalling to the main wall underneath, but, even so, the operation of renewing the finish would furnish adequate repairs for the main wall itself. On the other hand, if face brick or stone or ornamental terra cotta be spalled, the loss is total; the original finish can not be renewed, except by tearing the wall down and rebuilding it. On the interior, combustible trim of all kinds should be eliminated and marble or stone finish should be securely protected from the access of fire. Enameled bricks and enameled tiles should also be made secure against not only the direct access of fire but the effects of high temperatures however applied. Instead of marble wall finish or enameled bricks or tiles, wall plaster of a good quality, finished with enamel paint, furnishes a perfectly satisfactory substitute, so far as utility and sanitary qualities are concerned. If such finish is destroyed by fire, its renewal is a matter of relatively small cost.

All interior partitions should be so solidly constructed that there would be no question whatever of a fire ever getting through them. That ought to be absolutely impossible. Stairways, stairway halls, and other places where elevator grills, ornamental balustrades, etc., might be used should be so located that no fire would ever get into them, and they should be kept absolutely free of combustible matter

of all sorts and descriptions. Wooden floor finish should not be allowed in any portion of the building. All doors, door frames, window frames, and window sash should be of metal or of wood covered with metal. All important openings should have doors on both sides of the wall, the idea being to so design the interior of the building that a fire starting in any one room could be left to burn itself out not only without being communicated to other rooms or to the corridors, but also without causing any great money loss to the building itself in the room or rooms where the fire occurs. The interior construction of the building should be such that, should a fire by any chance be introduced from the outside, it could be confined absolutely to the room or rooms to which it finds access. Such a thing as a conflagration sweeping through a building can be made impossible at reasonable expense, provided unnecessary architectural finish is omitted and the money ordinarily expended on it is applied to other things.

Even such a building, however, might have a shutter left partly open, or some other of the various fire-resisting devices might be left in such condition as to defeat the purpose for which it was installed; so that if the building contains a large amount of combustible contents, it should still be provided with sprinklers. The municipal water supply should be under sufficient pressure to supply the sprinkler system. In a city like San Francisco an artesian well and fire pump in each building should be provided for the same purpose, if possible. Even then, if there is a conflagration raging, the mechanical staff of the building and as many more men as can be obtained should be kept on duty inside the building, watching for points of weakness and extinguishing fires should any begin. A small amount of water and a small force of men would suffice for this duty in a building constructed as described.

It appears that in San Francisco a number of owners who were organizing forces for the active defense of their buildings were driven out by the police and military authorities in accordance with instructions from the municipal authorities—no doubt to prevent looting and also with a view of saving people from the effects of the dynamiting. It would seem, however, that in some cases proper judgment was not exercised, and that some buildings might have been saved themselves and might also have acted as barriers to the further progress of the flames if their occupants had been permitted to carry out their plans. For good illustrations of what can be done in this way one need point only to the post-office building, the mint, and the appraisers' stores. There is also every reason to believe that a more or less active defense was carried on in the Kohl Building; otherwise it must have suffered more severely than it did. As it was, however, this building was saved with slight damage.

A fire-resisting building is, in one sense, exactly analogous to a fortification—it needs a garrison to make it thoroughly effective. There is this difference, however, that a fire-resisting building can be made so effective in itself that a relatively small garrison can save it. In my judgment, a building thoroughly well constructed along the lines indicated in this report would stand in a conflagration such as that which occurred in San Francisco, preserve its contents, and suffer a loss to its own structure and finish not exceeding 15 per cent. Until a result approximating this degree of endurance is achieved, it is hardly fair to say that the "modern fire-resisting building" is a success, except in so far as it enables a sufficiently tall structure to be erected on a piece of valuable real estate to furnish an adequate return for the entire investment, and even this statement is true only as long as the building does not happen to be attacked by a conflagration.

EARTHQUAKE INSURANCE.

It would seem that in a place like San Francisco it would be sound policy for the business men to form a mutual earthquake insurance company on lines similar to those of the mutual fire insurance companies. They should employ competent experts to draft specifications and evolve types of designs not in conflict with the municipal ordinances for buildings specially planned to resist earthquake. To be admitted to the benefits of the mutual earthquake insurance company an owner should be required to conform to the standard plans and specifications. In my judgment, there is every reason to believe that such an enterprise could be made successful and that it would result in having available at all times a fund for making good any earthquake damage. It is probable that the premiums that would have to be charged by such a mutual insurance company would be found to be no greater than those that are charged for fire risks in large cities.

SUMMARY.

It will be apparent that much of the information presented in a report like this one is necessarily hearsay. So far as the history of the fire is concerned, this indefiniteness can not be avoided, and the details of the damage itself could be verified only by a prolonged stay in the ruined city and a close inspection of the ruins of every building at every stage of the process of cleaning up. It is to be hoped that the technical men engaged on this work will keep a complete and accurate record of all details of every sort, which will be available for future reference. It is believed, however, that enough evidence was collected at first hand to abundantly justify every con-

clusion and broad statement contained in this report. The only doubt in my mind is whether the damage may not have been really greater than it appears.

Extreme caution should be observed in drawing general conclusions from any individual case of damage in a great conflagration. For instance, the way in which misleading conclusions can readily be reached is indicated in the discussion of the relative merits of terra cotta and concrete for fireproof floor construction. The records of the fire, rightly read, would prove that both concrete and burned clay are efficient as materials, but that the method of application of both is open to severe criticism. That hasty and ill-founded conclusions have been reached is only too evident from the articles which have appeared since the San Francisco disaster.

It is also necessary that extreme caution should be observed in drawing conclusions in regard to the effect of the earthquake. Reenforced concrete proved itself superior to brickwork beyond any doubt. There is every reason to believe that for buildings of moderate height reenforced concrete can be so designed that it will be quite as efficient as a steel frame; but it should be remembered that this proposition was not proved, because there was no reenforced-concrete building of considerable height in the entire district affected. Again, the fact that steel frames stood up during the earthquake does not prove that they are earthquake proof. The framing of the tower of the Union Ferry Building suffered almost fatal damage, yet it stood up. The Call Building proved the efficiency of stiff and adequate steel bracing; but many of the other commercial steel-skeleton buildings showed very clearly the need of it. The fact that some of the tall buildings are now out of plumb is no proof that they are damaged; very few such structures ever are plumb, and if the deviation is not very great it is quite possible, even probable, that the building was erected out of plumb. The condition of the masonry in wall piers, however, gives ground enough for uneasiness. It is safe to say that a well-braced steel frame is proof against ordinary earthquakes, but to point to the actual commercial steel-frame structure in San Francisco as a triumph of the ordinary type of steel frame, in advance of the careful detailed inspection of the steel work by competent engineers, is premature, to say the least.

THE EARTHQUAKE AND FIRE AND THEIR EFFECTS ON STRUCTURAL STEEL AND STEEL-FRAME BUILDINGS.

By Frank Soulé.

THE EARTHQUAKE.

GEOLOGIC FEATURES.

On the morning of April 18, 1906, central California experienced an earthquake, the most severe, as measured by its results, in the history of the State. The seismograph in the observatory of the University of California, at Berkeley, recorded the shock as beginning at 5 hours 12 minutes 6 seconds a. m., Pacific standard time, and as lasting for one minute and five seconds. Its severity was afterwards estimated and rated as IX in the Rossi-Forel scale of earthquake intensities. Other minor shocks followed immediately and at short intervals, so that before 7 p. m. of the same day thirty-one of these had been registered at the observatory. Slight shocks, coming successively after longer and longer intervals of time, were experienced during several weeks following, until finally the earth's crust in California seemed to have readjusted itself to new conditions of pressure and equilibrium. The material damage from the earth tremors was inflicted by the first great shock. The minor ones following wrought no injury, except to throw down a few tottering walls that had been racked by the original earthquake.

For many years the leading geologists in California have known that a rift, or line of dislocation in the earth's crust—called in common parlance an "earthquake crack"—starting near Point Arena, extends in a straight line, at least 400 miles in length, in a direction S. 35° E. (fig. 1, p. 3). Passing under the ocean bed 8 miles west of the Golden Gate, the rift cuts the shore again at Mussel Rock, runs along the reservoir basins of the Spring Valley Water Company and over the Coast Range of mountains, ignoring surface topography in its course, and extends at least to Mount Pinos, in Ventura County, and probably still farther to Lake Elsinore, in southern California. This great "fault" gives abundant geologic evidence of having been, in the remote past, the locus of many distinct earthquake movements and disturbances.

It was a rupture and slip along this fault, plainly evident for nearly 200 miles, that shook so violently the thousands of square miles of the earth's surface in central California. The first snap and movement of the crust were registered at the observatory of the State University as proceeding from south-southeast to north-northwest, or about parallel to the fault. This movement was there recorded as over 3 inches horizontally, and was accomplished, as estimated by the California earthquake investigation commission, in one second of time. The vertical movement at the same place and time was believed to be about 1 inch. Professor Omori, the distinguished Japanese seismologist, also estimated the vibration in San Francisco to be 3 inches in one second.

Instantly following this first snap were rebounds, reactions, and terranean reverberations from all parts of the greatly disturbed area on either side of the fault trace, which made the record on the seismograph resemble a tangled spider's web. It was this part of the earthquake—the temblors—that created and continued the racking vibrations, the twistings, and the wrenchings that brought down chimneys, walls, and towers.

Members of the California earthquake investigation commission advanced the belief that the first break, slip, and shock in the crust began at the northwest extremity of the fault trace, and that from this point the rupture and shearing extended progressively toward the southeast. This view seems to be borne out by later investigations, and certainly the greatest disturbances on the line of the fault were at and near its northern extremity. The earthquake was felt to a greater or less degree over a vast extent of territory, stretching from Coos Bay, in Oregon, to Los Angeles, in southern California, and from western Nevada over the greater part of middle California, and even out to sea. Although not noticeable to the senses, it was recorded on seismographs in Washington, D. C.; Tokyo, Japan; and Potsdam, Germany.

A STUDY OF THE EFFECT OF NATURAL FEATURES ON THE INTENSITY OF DESTRUCTION.

DISTANCE FROM THE FAULT LINE.

The actual area of destruction was about 400 miles long (from north to south) and 50 miles wide on either side of the fault trace. The destruction wrought by the earthquake in its severe effects was proportional in a way to the nearness of the locality to the fault trace, but varied greatly according to the character of the rock and soil formation throughout the disturbed area.

Directly on the fault trace the disturbance and destruction were at a maximum. Many buildings and other structures were wrenched,

twisted, and thrown down (Pl. X, *B*); fissures were opened in the earth (Pls. III, IV); trees were uprooted and thrown to the ground, or snapped off, leaving their stumps in a standing position, or split from the ground up through the stock to the branches (Pl. II). Roads were ruined for long distances, bridges were thrown off their abutments (Pl. XI, *A*), and water pipes were twisted, telescoped, collapsed, or broken (Pls. IX; X, *A*). Along the seashore immense landslides occurred, throwing vast quantities of earth and rock into the sea. (See also Pl. VIII, *B*.)

The main pipe lines of the Spring Valley Water Company, which were depended on exclusively to supply the city of San Francisco with water, as well as the distribution system of this company in the city, were broken in many places, and the supply of water was absolutely cut off for a number of days after the earthquake (map Pl. LVI). The great mains leading from Pilarcitos, San Andreas, and Crystal Springs lakes were all badly broken (Pl. LVII). The Pilarcitos conduit in particular, which ran almost along the fault trace, was completely ruined and rendered unfit for repair (Pl. IX). The great 44-inch water main crossing the San Bruno marsh was thrown down from its supporting trestles in a serpentine line, and broken in several places.

As the distance from the fault trace increased, the violence of the disturbance in a general way diminished, but this statement must be modified by saying that in cities and towns built upon the alluvial soil of valleys the destruction was at its greatest, as, for instance, at Santa Rosa, about 20 miles east of the fault trace, in the Sonoma Valley (Pls. XIV, *B*; XVII, *A*). This city, built upon a deep, alluvial soil, was more severely shaken and suffered greater damage, in proportion to its size, than any other town in the State. Scarcely a brick or stone building in the town was left standing, and 80 people were killed.

SOIL FORMATION.

The destruction wrought by the earthquake amounted to little or nothing in well-built structures resting upon solid rock, and, all other things being equal, increased in proportion to the depth and incoherent quality of the foundation soil. Thus dwellings in Berkeley, upon the solid rock, were scarcely disturbed, while those on the level plain of Oakland, 4 miles distant, were severely shaken and injured, as, also, were the buildings at Leland Stanford Junior University (Pls. XIV, *A*; XV; XVI; XVII, *B*; XVIII), 7 miles distant from the fault trace; at San Jose (Pls. XII, *B*; XIII, *B*), 13 miles distant; and at Agnew (Pl. XIII, *A*), 12 miles distant. The town of Salinas and the alluvial valley of Salinas River were also severely shaken. This region was fissured and disturbed more than any other district in the State.

In order to get a fair understanding of the effects of the earthquake in San Francisco, a knowledge of the geologic formation and the different soils constituting the foundations of structures is necessary. The city and county of San Francisco comprise the northern extremity of a long, narrow peninsula, lying south of the Golden Gate, between the Pacific Ocean on the west and the southern half of San Francisco Bay on the east. (See map, Pl. LVII.) The boundary line between this county and San Mateo County lies about 8 miles south of the Golden Gate. The area of San Francisco County is 46½ square miles. The population of the city on April 1, 1906, was estimated to be 460,000.

The site of the city has at least four different soil formations. Around the Bay of San Francisco, from Telegraph Hill to Mission Creek, which runs from west to east and empties into the bay, and on both shores of the creek is a strip which was originally mud flats and overflowed lands, having an area of about 354 acres. These tracts have been gradually filled in (especially on the bay shore and the northern Mission Creek sides), since the days of the American occupation, by encroachments on the water front, due to business and commercial pressure, and wharves and docks, warehouses, factories, manufacturing establishments, and large wholesale houses have been built on these filled-in lands. At the present time these large areas are for the most part included within the sea walls running around the officially established water front nearly as far as Mission Creek. They are known as "made lands," and consist of deep layers of mud, in many places saturated with salt water, and overlain by sand, trash, etc., which has been filled in upon them.

On this soil were built nearly all the commercial and wholesale business structures of San Francisco—such as the Union Ferry Building—many large hotels, the post-office, the branch mint, and similar structures. On the Mission Creek side were originally very large areas of marshes that have been filled in with sand from adjacent hills. Adjoining all these made lands is the comparatively level ground, composed of a natural mixture of sand and clay, formed by the wearing of the hillsides and by the incoming of sands drifted from the seacoast. Upon this fringe of soil next to the made lands were built many of the largest hotels, tall office buildings, and expensive structures of brick, stone, and steel.

A ridge of rocky hills runs from the northeast corner of the city, or Telegraph Hill, southwestward along Russian Hill, Clay Street Hill, and so on, to Sutro Heights. These hills are composed largely of indurated clay, shale, and, on their highest summits, serpentine and other rocky formations. A ridge of sand hills runs through the western and southwestern portions of the city to the Pacific Ocean. The slopes and summits of the hills nearest the business portion of

the city are closely built residence districts, and the areas toward the Pacific Ocean are covered with cottages, more and more sparsely placed, to the boundaries of the county.

Adjoining the business district on the southwest side, along Mission Creek, on the flat sand lots, was another thickly populated residence section known as "south of Market street." It was occupied almost exclusively by wooden buildings.

More than 90 per cent of the buildings in San Francisco were of wood. Almost all the brick, stone, and steel structures were in the congested business portions of the city, upon or very near the made land. Even in this district there was a large percentage of wooden buildings. High steel structures of the most modern type have been erected only recently in San Francisco, and the number of them is small, not exceeding 50.

The most destructive effects of the earthquake in San Francisco were experienced upon this made land. Wherever buildings were well founded on wooden piles deeply driven into the mud—as, for example, the Union Ferry Building—these foundations were disturbed but little or not at all; and where the superstructure had been well and strongly put up, practically no damage resulted. Only in poor foundations laid directly upon "filled-in" ground on the raft principle, or in buildings that were poorly constructed or underpinned or had a weak frame, poor brickwork, or brick laid dry in poor lime mortar, was there serious damage or collapse.

The Union Ferry Building (Pl. XLVI, A), with the exception of its high tower, was little injured, and the level of its floors was not perceptibly changed. At the same time, the streets at its front, which rested simply on the made soil, were rolled into waves 3 or 4 feet in height. So far as the writer is aware no foundations that had been properly established were in any considerable degree injured by the earthquake; nor was any structure of brick or stone, iron or steel, that was well designed and constructed, greatly damaged. Some chimneys and cornices were thrown down, but until the fire had passed over the region the structures remained ready for use. This statement applies especially to the wooden-frame structures throughout the residence part of the city, where the only losses were those of chimneys and plaster.

On the made land in the business portion of the city there had been erected in early days many light wooden buildings, which rested on simple timber underpinning founded on the filled-in material. Many of these structures collapsed, but this result was due to their imperfect foundations and weak construction rather than to the severity of the earthquake. Numerous structures in this district had been built of dry brick or stone laid in common lime mortar, and their beams, girders, and columns had not been anchored to the

walls. Such walls commonly collapsed, and the brick were found afterwards with dry, clean surfaces, the mortar having no adhesion. (See Pl. XXI, *A*.) On the other hand, walls that had been laid in Portland-cement mortar, with brick thoroughly wetted and all parts well bonded together, stood the trial perfectly and are standing to-day.

Tall, steel-frame, stone-exterior office buildings of the class A type that were founded either on well-driven piles or on concrete slabs suffered no very serious injury by the earthquake. With the exception of a crack here and there in a stone pier, arch, or stairway, or a block of veneer loosened or dropped from a front, they remained entirely serviceable, so far as the earthquake effect was concerned. An excellent example of this class of buildings, and one that is exceedingly instructive, as it passed through the earthquake but escaped the fire that ravaged San Francisco, is the Union Savings Bank, in Oakland, at the corner of Broadway and Thirteenth street. This building is a steel-frame, stone-veneered structure, having 11 stories and a basement. It is founded upon separate concrete blocks and piers which rest upon a strong soil of mixed sand and clay. This structure was practically uninjured.

Buildings in San Francisco which rested upon foundations of sand in natural place were not injured by the shock, except where the sand was on a hillside or had opportunity to spread and flow. In such places buildings of either masonry or wood were badly shaken. Where the buildings rested upon good, hard soil, as on the hillsides or summits, practically no injury was done with the exception of the loss of chimneys and, in some buildings, of plaster. A first-class building of stone, brick, concrete, or steel frame in such situation seems absolutely proof against any earthquake of no greater severity than the one under discussion.

THE FIRE.

GENERAL DESCRIPTION.

Immediately after the first shock of the earthquake sixteen alarms of fire, from widely separated localities, were turned in to the central station. The causes of these fires were directly traceable to earthquake effects, such as the upsetting of oil lamps and oil and gasoline stoves, the contact of combustible material with lamps and gas jets, the rupturing of chimneys and flues, the scattering of chemicals, such as phosphorus, and the upsetting of boilers, furnaces, etc. It is claimed that currents of electricity did not originate any fire. Either the generators were disabled or the attendants switched off the currents.

The death of Mr. Sullivan, the chief of the fire department, which was caused by the falling of a mass of brick from a chimney while he lay ill in bed, was a most unfortunate accident, as the city was thereby deprived of his excellent knowledge and skill as a fire fighter. The fire department, although it responded promptly to the calls and was composed of brave and efficient men, with excellent apparatus, was disconcerted by the loss of its chief and paralyzed in its action by the almost complete rupture and disintegration of the water system. The city mains were so thoroughly broken that in a short time not only could no water be obtained for the extinguishment of fires, but for a number of days little water could be had for domestic use, and the people were compelled to rely on a few wells that remained available.

In private dwellings incipient fires were quickly extinguished by individual effort; but, because of the early hour, the fires which started in the great downtown business houses, factories, etc., "south of Market street," grew to alarming proportions before anyone could reach and conquer them. With the exception of the private water supplies, such as wells (see map, Pl. LVI), pumping systems, etc., possessed by a few establishments, there were no means of extinguishment. Within three hours after the earthquake nine fires were in full conflagration between "The Mission"[a] and the water front south of Market street. At first there was little or no wind to fan the flames, but the great heat soon drew in a current of air which continually increased, and, varying from one point to another, swept the flames first in this direction and then in that. By Wednesday noon the fire had consumed nearly a square mile of the city on the south side of Market street, and on the afternoon of the same day it broke across to the north side, in the vicinity of the high steel Call (Claus Spreckels), Examiner, and Chronicle buildings. Thence the fire veered with the wind, burning northward and westward through Chinatown, and joined its destructive energy with that of a separate column of fire that had swept up from the lower end of Market street and the water front. The column, driven by the wind, ate its way rapidly through the residence portion of the city, which was built of wood and hence was consumed like tinder. Three hours after the conflagration had begun a corps of dynamiters was organized, but as no such body had existed in the fire department, it was necessarily composed of volunteers and amateurs. These men fought the flames with great bravery, but with little skill, and their endeavors to arrest the progress of the fire by throwing structures down in its path were

[a] "The Mission" is a well-known locality in the city of San Francisco. It is the site of the original settlement and mission established by the Franciscan monks, and the old Mission Church still stands there (Pl. XXIII, *B*), as the fire was checked at this point just in time to save it.

futile until late on Thursday night, after a dynamite expert had been put in charge. A last stand was made in the western part of the city, at the broad and open street, Van Ness avenue. Here the dynamiters, aided by the shifting of the wind to the west, were able to stay the progress of the fire. Everything in the Mission district had been burned, except at places where the flames were checked by means of private water supplies. Although comparatively feeble, the fire continued in some parts of the desolated district until Saturday morning, April 22, when the last blaze was extinguished. The wharves and a fringe of buildings along the water front had been saved by means of engines and State fire boats drawing water from the bay.

The area of the burned district (see Pl. LVI) is 4.05 square miles, or 2,593 acres, and includes 490 blocks entirely burned and 32 blocks partially burned. These blocks were in two different classes, one being the "100-vara [a] block," and the other the "50-vara." Some structures along Mission Creek and a few residences on the summits of Telegraph, Russian, and Clay Street hills (Pl. LIV) escaped. The mint and a few other buildings were also saved by means of private water supplies.

Thus the greatest fire in the history of the world destroyed more than 4 square miles of closely built city property estimated at $500,-000,000, half of which was insured; with the loss, it is believed, of about 800 human lives (though the official count is less).

San Francisco was little prepared to fight a conflagration under the existing conditions. Ever since the six devastating fires of the period from 1849 to 1852 the people had evidently relied on the excellence of the fire department (subsequently organized), the damp atmosphere, and the tradition that redwood, which composed the exterior of 90 per cent of the structures, would not burn. Dwellings were not protected against fire either from within or without, and the same may be said of most of the boarding houses and even of some of the public hotels. There were few chemical extinguishers, private water supplies, or other fire apparatus in existence. In the congested business district buildings that had ample modern means of fire prevention within, or protection against fire from without, were the exception rather than the rule. Few buildings had metal shutters, wire-glass windows, sprinkler systems (interior or exterior), or private wells, tanks, or pumps. Some buildings where these preventives were installed were saved, although surrounded by fire.

Inflammable wooden buildings—remnants of the pioneer days of 1849—were scattered through the business districts and added fuel to the flames. The magnificent high steel structures that were gutted

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[a] The vara is the Spanish unit of length, and equals 33.38 inches.

by the fire owe their desolation for the most part to their environment by these inflammable buildings.

There was no dynamiting corps in the fire deparment and no adequate salt-water system for fighting fires, although the city was almost surrounded by salt water, and there were no fire boats belonging to the department, and few cisterns in the streets or squares. Most of the streets were very narrow, and many of them were lined by high wooden buildings. With the water mains and distribution system incapacitated by the earthquake, it is no wonder that the city burned; the only wonder is that it had not burned before. This result had been prophesied by insurance inspectors many months previously.

ABSTRACT OF REPORT OF ENGINEERS' COMMITTEE OF THE NATIONAL BOARD OF FIRE UNDERWRITERS.

The Coast Review, an insurance paper, gives an abstract of the report and conclusions of the engineers' committee of the National Board of Fire Underwriters. This report was published in October, 1905, many months preceding the occurrence of the great fire, and is epitomized as follows:

The area of San Francisco within the "fire limits" was 1.6 square miles. The "brick district" comprehended 0.95 square mile, and the "congested-value district" 0.49 square mile. The number of fires in the preceding nine years was moderate, but the average loss at each fire was two or three times the loss expected in cities having ordinary fire protection. The water supply was satisfactory in many respects, although the pressure (the average being 52 pounds) was too low for automatic sprinkler equipments, standpipes, etc. The fire hydrants were of an old style, and many water mains were too small. There were four water services, varying for districts of different levels. It was stated that the fire department was satisfactory in most respects, but that the building laws were not enforced thoroughly and impartially. The fire-alarm system was criticised adversely.

The "congested-value district" was bounded on the north by a mixed mercantile, warehouse, and dwelling section; on the west by a fashionable boarding-house, apartment, and residence district; on the south by a compactly built mixed district composed of dwellings and manufacturing and mercantile buildings, and on the east by the Bay of San Francisco. This district consisted of 101 blocks, containing 2,086 separate buildings, of which 2.2 per cent were fireproof, 68.3 were joisted brick, and 29.5 were frame buildings. There was only one sprinkler equipment in the district, and it was practically obsolete. Premises were generally clean and well cared for.

The "potential hazard" in the produce and commission district bounded by Battery, Washington, Drumm, and Commercial streets was said to be serious. The expert inspectors claimed to have found

"conflagration breeders." In regard to the blocks north of Market street and between Powell and Taylor streets they reported: "This section contains more serious exposures and conflagration breeders than any other equal area in the city." They reported "frequent high winds," the absence of modern protective devices generally, the "probability feature" alarmingly severe, the elements of a "conflagration hazard" present to a marked degree, and the topography unfavorable. In fact, "San Francisco has violated all underwriting traditions and precedents by not burning up; that it has not done so is largely due to the vigilance of the fire department, which can not be relied upon indefinitely to stave off the inevitable."

This report was locally regarded as very severe, and in some respects—for instance, when referring to winds, redwood lumber, and hilly topography being unfavorable—as erroneous; but, unfortunately for San Francisco, the prophecy has come true.

EXTRACT FROM A SAN FRANCISCO FIRE EXPERT'S REPORT TO THE BRITISH FIRE-PREVENTION COMMITTEE.

George J. Wellington, who was born and reared in San Francsico, and therefore can not be accused of prejudice against that city, in his report to the British fire-prevention committee of London in 1906, says, among other things:

> A glance at the city from a point of eminence shortly after the temblor had subsided at once disclosed the fact that San Francisco was doomed. Columns of smoke ascending from fires at many different points made apparent a condition that no fire department in existence could cope with, on account of the impossibility of assembling sufficient apparatus at each fire to control it, and particularly on account of the fact that there was little or no pressure in the hydrants. . . . Observation for six hours from the top of a tall office building failed to illustrate anything not already known to fire experts, and previously demonstrated at Baltimore and other places. Unprotected openings of brick buildings, improperly hung and uncared-for metal-clad shutters, ineffective rolling and ordinary iron shutters, were conspicuous by their weakness. Exposed sides of hollow-tile fireproofing again cracked away; concealed piping again forced fireproofing away from steel members that it was intended to protect; metal-lath and plaster partitions again failed, and unprotected steel was warped and distorted, permitting floors to fall. Tall brick buildings with joisted interiors radiated heat to wooden cornices and window frames, which took fire. . . . In fact, everything that had been predicted by fire engineers occurred.
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> The bigotry of architects, the cupidity of contractors, and the penuriousness of owners have laid the metropolis of the Pacific low. The work of intelligent architects came to naught against the creations of incompetent ones. The owners of well-constructed buildings were burned out by their criminally careless neighbors. In many instances talent was not engaged on account of its ability to construct permanently and well, but rather for its shrewdness in erecting structures that would earn the greatest returns for sums invested. Competi-

tion in this respect has led to the use of inferior materials and the evasion of building laws and the underwriters' recommendations. San Francisco possesses building laws in plenty, which require enforcement rather than alteration. A valuable addition to present ordinances would be one similar to that in force in some European countries, which penalizes owners for fires that escape from their buildings, affording protection to men disposed to build well.

EFFECT OF THE LAYOUT OF THE CITY AND THE CHARACTER OF THE BUILDINGS.

San Francisco, as already stated, is divided into three great districts. Market street, the great artery of the city, 120 feet wide, runs southwestward from the bay, and divides the city into two parts—first, a level district on the south, largely filled with wooden buildings, factories, foundries, lodging houses, and the like, but around the bay extremity of the street covered to a considerable extent with buildings of brick, stone, or steel frame; second, the uneven and in its remoter parts hilly district on the north. This northerly portion is subdivided by Van Ness avenue, which separates the older residence district from the newer one on the west.

In the older section of the city, between Market street and Van Ness avenue, the streets had been established under the old Spanish system of "100-vara lots," as they are locally known, each block containing about 76,000 square feet. West of Van Ness avenue and south of Market street, in parts of the city more recently surveyed and built upon, the blocks are much larger, and—particularly along Market, Mission, and adjacent streets to the south—were built up with very long rows of buildings, many of them continuous for hundreds of feet. These blocks were so large that it was found necessary, or at least convenient, to subdivide many of them by narrow streets or alleys that permitted the ingress and egress of carts and drays. It was easy for the flames to pass across these narrow streets, and the heat was in many places so great that buildings on the opposite side of the street were ignited by the heated air without the passage of any flames.

More than 90 per cent of the buildings in San Francisco were of wooden-frame construction, and many of the new, modern, and so-called "fireproof" buildings were surrounded by frame structures of an old type, and, of course, were injured or destroyed by their combustion. The fire limits permitted these wooden structures to approach rather close to the business section; and in the congested business district at least 30 per cent of the buildings were of frame construction, some of them four or five stories in height. Outside of the congested district many business houses and almost all dwellings were frame structures, and except in the out-skirts of the city

were closely built in long rows extending over entire blocks. In the business district almost every separate structure was close to its neighbors. Wide, uncovered spaces separating buildings were, as a rule, confined to the outlying suburbs. In the compactly built district of wooden structures a house every three minutes was frequently the rate of destruction from the fire during the high wind that prevailed at times.

In the congested business district about 75 per cent of the streets were 60 feet wide, and a few (about 30 per cent) were at least 80 feet wide. These streets offered very little obstruction to the passage of the flames or heated air, and it was aided by the winds that were caused largely by the conflagration.

The height limit as established by the city ordinances was 220 feet for buildings of class A, 100 feet for class B, 82 feet for class C, and 45 feet for frame buildings. Brick buildings with wooden joists were therefore allowed to be built to a height of eight stories if furnished with wire-lath and plaster ceilings, thus affording the fire admirable opportunities for destruction.

BEHAVIOR OF STRUCTURAL STEEL AND STEEL-FRAME BUILDINGS SUBJECTED TO THE EARTHQUAKE AND FIRE.

EFFECTS DUE PRIMARILY TO THE EARTHQUAKE.

INTRODUCTION.

Structural steel as a building material and as a principal stress resistant in high steel-frame buildings has greatly increased in favor since its entirely satisfactory behavior in the recent great vibrations in California; for while it possessed strength and stiffness to a satisfactory degree, it also displayed an amount of elasticity that avoided much shearing and fracture, even under the vibrations of the tallest steel-frame structures.

The behavior of structures of the various types in San Francisco and elsewhere in the area destructively affected by the earthquake was in strict accordance with the merits of their foundations, design, materials, and workmanship. The so-called fireproof buildings within the area most affected by the earthquake, and afterwards, in San Francisco, burned over, did not exceed 60 in number. Among these buildings were 8 having steel frames and hollow-tile floor arches, 29 or 30 having steel frames with reenforced-concrete floor arches, and 2 having reenforced-concrete frames—one of these of imperfect design. There were 6 unfinished buildings with steel frames, and 10 having brick walls and fireproof floor arches.

FOUNDATIONS.

It is believed that every building whose foundations were well and strongly established—upon deep piling, as the Union Ferry Building and the Merchants' Exchange; with reenforced-concrete slab, as the Call Building; upon separate concrete piers or grillages resting upon good beds having a uniform load per square foot, as the Union Savings Bank in Oakland; or upon any other type of excellent foundation—escaped injury by the earthquake to the foundations themselves, nor did the superstructure owe any damage to inefficiency in those foundations.

The central portion of California was subjected to a severe earthquake in 1868, and has, on a number of occasions since, been slightly shaken by earthquake shocks, but many architects and engineers, and the people generally, had become so accustomed to these slight movements of the earth's crust that little attention was paid to them, and, so far as the writer can learn, architects had believed that in establishing solid foundations for high steel buildings, with good anchorage and bracing, adequate to take care of extreme wind force, they had sufficiently guarded against the effects of any earthquake vibrations which might occur. As a matter of fact, the provisions thus made seem to have been ample and safe so far as any disturbance of the foundations or any lack of support of the superstructure has been detected. Notwithstanding the severe vibrations these tall buildings have been called upon to endure, they have remained plumb and very slightly damaged by the earthquake.

STRUCTURAL-STEEL FRAMES EXPOSED TO VIBRATORY MOTION.

As stated by A. O. Leuschner, secretary of the California earthquake commission, and also by Professor Omori, the distinguished seismologist of Japan, the vibratory motion in Berkeley and in San Francisco was approximately 3 inches in a horizontal direction and about 1 inch vertically, the time of the first oscillation being one second. This is understood to be the vibration on very hard soil or solid rock. Where the soil was softer and less coherent the waves became longer and the movement slower.

This vibratory motion had a tendency to move the foundation of a high building and the basement immediately in connection with it forward and back, and perhaps to move some of its columns in opposite directions, although this is not certain. At any rate, it apparently had the effect, owing to the inertia of the mass of the upper part of the building, of bringing a maximum bending moment to bear on the frame at some point between the basement and the top

of the building—to speak roughly, somewhere near the middle stories. It also seemed to have the effect of producing a horizontal shearing stress in the frame, particularly above and near the basement. The frames in these high buildings seemed to be the most severely wrenched, and the exterior walls, stairways, linings, etc., most injuriously cracked in these middle stories. For example, the magnificent eighteen-story Call Building seemed to be well braced against bending moment and shear, but the eyebars from the tenth to the sixteenth floor and the transverse wind bracing are reported to be somewhat buckled, the maximum occurring on the thirteenth floor. The braces were warped on all four sides of the building, and there was also probably some slight distortion of the steel frame from the tenth to the thirteenth floors. The exterior veneer of stone remained practically intact up to the tenth floor, above which, up to the sixteenth, there was an increasing amount of damage, some of the stone being considerably out of place. (See also p. 146.) The same thing practically can be said of the new Chronicle Building, the damage to the stonework of which can be noted by a close inspection of Pl. XXX, *B*. The earthquake proved the absolute necessity of bracing steel-frame buildings with diagonal braces, so far as the requirements of use will allow. The Mutual Savings Bank and the Shreve and Atlas high steel-frame buildings have such bracing and remained entirely plumb after the earthquake. The St. Francis Hotel and the Call Building were somewhat similarly braced and were also left in reasonably good condition.

Some architectural authorities assert that wind bracing put in liberally for an allowance of 30 pounds pressure per square foot will amply care for earthquake vibrations of an intensity equal to those of April 18, 1906. Undoubtedly many of the high steel buildings in San Francisco were designed without reference to earthquakes, but they have nobly withstood their effects, and steel frames have proved themselves entirely adapted to earthquake countries. A careful inspection of the high steel frames in San Francisco shows that they suffered comparatively little injury, and that this injury was confined to the shearing of rivets and connections, particularly in the lower stories and on the ground floors, and to some buckling of braces.

After the earthquake, bolts and rivets in the Union Trust Building were found to be loose, and some were sheared off. This damage was due apparently to faulty construction, careless workmanship, and the insertion of field bolts, in some places, instead of rivets. It was shown that the rivets, connection joints, etc., in these steel-frame structures are of vital importance, and that in order to resist earthquake vibrations they should be made as strong and effective as possible, particularly at the basement and first floor.

MASONRY WALLS AND STONEWORK.

The stone exteriors of all the high steel-frame buildings were to a greater or less extent cracked or injured under the action of the earthquake. In some places, owing probably to imperfect bond between the veneer and the steel frame, the stone veneer was displaced and the walls were bulged outward; in others, blocks were thrown to the ground and bricks or arch stones from windows and other exterior openings were dropped out of place. This disintegrating effect had its maximum in the intermediate stories between the top and the base of the building, a very good example being the Union Savings Bank in Oakland. This eleven-story steel-frame, stone-veneer structure gave opportunity for careful and comprehensive study of earthquake effects independently of fire, since it is really the only high steel-frame structure in the disturbed area which was not subjected to fire. In this building the steel frame is intact and uninjured, so far as can be ascertained. The marble veneer along the stairways and corridors and the sandstone exterior, particularly in the fourth, fifth, sixth, and seventh stories, were somewhat cracked and disturbed, indicating not only a bending but a shearing action; and the brick in the arches in some of the windows in these stories have dropped to the ground. Otherwise the building escaped damage, and it has been continuously in use since the earthquake.

The Aronson Building, at Third and Mission streets, had stone piers running from the bed up to the street level. These were badly wrenched and cracked by sheer action, and in the ninth story two courses of stone in the arches above the soffit course were badly cracked, apparently for the same reason. In the Call Building, where the stonework ends at the sidewalk level, the corner piers were not found to be cracked, but in the James Flood Building (Pls. XXXIII, *B*; XXXV, *A*), where the stonework extends to the bottom of the basement, the corner piers were cracked by earthquake action.

RELIABILITY OF STRUCTURAL STEEL.

Structural steel is a very reliable material. It is produced and also placed in position by high-class skilled labor and is not subject to the flaws which sometimes appear in concrete work as a result of poor quality of labor and inefficient inspection. Builders in this country have had much experience in the use of structural steel, and feel sure of what it will do and for what it stands. It is no longer in the experimental stage as to resistance either to earthquake tremors or, when properly fireproofed, to conflagration. Constructors in San Francisco feel that this material has safely and triumphantly passed through a most trying ordeal.

EFFECTS OF THE FIRE.

BUILDINGS.

Structural steel in the steel-frame buildings subjected to the terrific heat of the great conflagration behaved satisfactorily wherever it was properly and amply protected by any method adopted for fireproofing. In no instance that has come under the observation of the writer has the steel been injured or deformed where such fireproofing was of the proper kind and remained intact after the earthquake. Unfortunately, in many places there was practically no fireproofing whatever, or it was very poor in design or workmanship, or both, and as a consequence failed miserably. Columns were softened and buckled. Girders were softened to such a degree that they sank by their own weight, some pulling after them the walls into which they were built, others falling into the fiery furnace below, as in the Cowell Building (Pl. LI, *B*), where the fireproofing either was lacking or proved defective in the fire. In such places the columns were buckled and some of them telescoped, thus removing all support for the floors above. In other buildings where the fireproofing was fairly good and effective, as in the James Flood and the Call buildings, the structure remained ready for rehabilitation. Although all the steel girders or columns that were subjected to intense heat on account of lack of fireproofing did not fall, yet many of them were rendered unfit for further use.

Prominent among the steel structures was the eighteen-story Call Building; with dome and lantern, the architectural pride of the city. This building took fire through a tunnel leading from the power house in the rear of the building, across Stevenson street. The fire was drawn in by the draft up the 18 stories of the elevator shaft, which acted like an enormous chimney, the flames being sucked up to the topmost story with great force and rapidity. The heat, of course, became intense, and all combustible matter on the interior of the building was quickly consumed, but the fireproofing, although not perfect in design and execution, so far protected the steel frame that it remained only slightly damaged and ready for refitting. The marble lining of the walls and corridors, and the glass in the exterior and interior windows, were all destroyed, and the metal trimmings were to a considerable extent melted or ruined. But the steel frame and stone exterior, with the exception of that on some of the middle stories, remains little injured, and parts of the building are continuously in use.

In the same way the James Flood Building, one of the newest and largest steel-frame structures, excellent in design and first-class in workmanship, was fairly well fireproofed; and although gutted by

the fire, it is being rapidly refitted for store and office occupation. The Western Pacific Bank reoccupied its old quarters on the first floor of this building almost immediately after the fire.

FIREPROOFING.

GENERAL CONDITIONS.

It can be truthfully stated that perfect fireproofing of buildings in San Francisco, even in those of the newest and most modern type, was the exception and not the rule. The bent or broken columns and the distorted or disfigured steel girders in many of the burned buildings demonstrate this fact (Pl. XXVII, *B*). Wherever structural-steel framework was covered with fireproofing material of the best design, executed with conscientious, skillful workmanship, the steel remained uninjured after the fire.

The lessons taught by the great Chicago and Baltimore fires had been applied by but few of the architects of San Francisco, on account of cost restrictions insisted on by owners, and very much of the damage inflicted on these high-class structures during the conflagration is directly traceable to the imperfect fireproofing put in, or to the entire absence of fireproofing. Some of the failures were evidently and directly attributable to poor workmanship.

CONCRETE.

There are two opposing parties in the matter of fireproofing in San Francisco—those who have favored the hollow-tile system, and those who believe in concrete as the best fireproofing material. The Bekins Van and Storage Company's warehouse, the only building of considerable size in the city constructed of reenforced concrete, has already been mentioned as resisting the action of the earthquake and fire. In this building the concrete acted as a perfect fireproofing protection for the steel.

Good Portland-cement concrete has won a triumph for itself in fireproofing in San Francisco, for wherever well made and properly laid upon the steel girders or columns, it protected the metal. In very hot fires the exterior portions were disintegrated, and in some places the whole mass was cracked, necessitating removal, but the fireproofing it furnished during the conflagration was excellent. Examination showed also that it protected well against rust. The heat to which it was subjected was very great, in places common mortar being fused and ironwork in walls melted.

The steel beams and girders in the St. Francis Hotel, the Merchants' Exchange, the Mutual Savings Bank, and other similar structures that were thoroughly fireproofed with concrete endured the fire exceedingly well.

The weight of Portland-cement concrete is a drawback, and, moreover, concrete is expensive when well made and applied. Cinder concrete was well esteemed for fireproofing for floors, but the scarcity of good cinders in the city rendered its general employment impracticable.

TERRA COTTA.

As fireproofing for floors terra-cotta tiling has not given universal satisfaction. It is lighter than concrete, but the wrenching of buildings during the earthquake opened many of the joints and the mortar was destroyed—as in the Mills Building, a large ten-story steel-frame structure of the older type, having self-supporting walls. The mortar joints in the tiling were started by the earthquake, and the mortar was disintegrated by the fire, the floors being destroyed and the lower surfaces of the tiling badly spalled. The same effect was noticeable to a certain extent in the excellent Union Trust, Crocker, and James Flood buildings. In the last named the flooring was fireproofed with terra-cotta arched tiles, covered with concrete on top and finished beneath by an efficient ceiling plastered on wire lath. The fireproofing was less injured in this building than in almost any other.

Terra-cotta fireproofing of columns was in many buildings a failure, not so much on account of the nature of the material as because of its insufficiency in quantity and poor or imperfect method of application. Wooden studs were in many places put behind the terra cotta. These burned out quickly, leaving the material unsupported. Pipes and wires were run up between the column and the fireproofing, and the twisting or expansion of the pipes caused by the earthquake movement broke the protecting cover. Imperfect junctions with ceilings above or floors beneath were common. That such imperfect construction should never be adopted has been fully demonstrated in San Francisco.

Porous terra cotta has been found more satisfactory than the hard and glazed varieties. For inclosing columns, the round porous forms have proved more stable and efficient than the rectangular ones, as shown in the Spring Valley Water Company's building (Pl. XLV, *A*) and the Aronson Building (Pl. XXVII, *B*).

PLASTER AND METAL WORK.

Common plaster on wire mesh, metal lath, or expanded metal was very generally used for the fireproofing of columns, partitions, and the like, on account of its cheapness, but was a failure when subjected to a hot fire, as proved in the Hotel Fairmount (Pl. XXXIV), the Hotel Hamilton, and several other buildings. This failure was much more noticeable where only a single wrapping or thickness of the wire

mesh, etc., was used than with the double wrapping. But even the latter proved to be too weak and disintegrable to pass successfully through a severe earthquake or a fire and a strong stream of water from a fire hose. The plaster quickly cracks and falls away from the metal. No doubt these materials will be used in the future by owners demanding cheapness of construction, but they will satisfy the requirements only in cases of mild exposure. Good gravel concrete in place of the plaster, if of considerable thickness, has been found to give better results.

The failure of the plaster and metal method and some other methods of fireproofing in San Francisco is directly traceable to the commands of owners to their architects to cheapen as far as practicable the fireproofing and the construction generally, in order to receive greater interest on their investments. Much of this cheapening has been done in spite of the protests of the designer, and it is in an entirely wrong direction; for rates of insurance are largely reduced with improvements in fireproofing, and as the cost of the steel frame and its proper fireproofing seldom exceeds 27 per cent of the cost of the building, it seems wise to protect the other 73 per cent with adequate materials.

BRICKWORK.

In some buildings in San Francisco, brick laid in rich Portland-cement mortar has been found to be an excellent fireproof covering; but it is objectionable on account of the bulkiness of the brick and the rusting of the steel, as in basement stories. Good brick withstood the severe fire well, and where laid in rich cement afforded a strong fireproof wall or pier. At least 4 inches of brickwork was found necessary, and a layer of concrete 3 inches in thickness between that and the steel was a great improvement and served well to protect the steel from rust. But this method will probably not be followed in general, on account of weight, bulk, and expense. Hollow brick and tiling were efficient also when properly and liberally used, porous tiles proving to be the better.

The well-known Palace Hotel was built about thirty years ago, a few years after the earthquake of 1868, and before the introduction of steel-frame structures and concrete steel. It was intended to be earthquake proof as well as fireproof, and was built with very heavy walls of brick, most of them being 2 feet or more in thickness, laid in cement mortar, and strongly braced by many cross and partition walls. In the brickwork, at every 3 or 4 feet in height, were laid bands of iron, riveted together at their ends and crossings. This building, although of the old type, successfully endured the great earthquake, its walls being practically uninjured (Pl. XXX, *B*);

and although gutted by the fire, which gained access through the unprotected windows and wooden casings, was so strong on its foundations that very vigorous blasting operations were required to throw down its walls.

REENFORCED CONCRETE.

There was in San Francisco at the time of the earthquake only one building of considerable size constructed of reenforced concrete. This fact was due to the opposition of certain labor unions to the use of this material in place of brick and stone.

The building referred to is that of the Bekins Van and Storage Company, at 190 West Mission street (Pl. XXVII, *A*). This building had outside walls of brick, but was massively constructed on the interior with columns, beams, and floors of reenforced concrete. It was originally intended to carry it to a height of four stories, but on account of the earthquake, which occurred during construction, the building was finished to include only the second story. At the time of the fire the permanent doors of iron were not in place, and the fire gained access to the front or south room, where very slight damage was inflicted. The entire main interior and the goods stored therein were unharmed, and the building has been in continuous use since completion. The brick building adjoining, however, was badly injured by the earthquake and was afterwards burned.

LESSONS FROM THE VARIOUS TYPES OF BUILDINGS.

Great destructive earthquakes have seldom occurred twice in the same locality during centuries of time, but, so far as man knows, one may occur at any time anywhere on the earth's surface. On the other hand, destructive conflagrations in cities have happened many times, but most of them might have been avoided by wise and adequate provision for fire prevention, protection, and extinguishment.

In San Francisco the earthquake could not have been averted, but its disastrous effects on structures could have been prevented by the use of proper materials correctly applied in the execution of skillful and scientific designs, carried out by good conscientious workmen under honest and able supervision. The city's official inspection has usually been very inefficient.

The buildings in California that were ruined or badly injured by the last earthquake may be divided into four classes:

The first class comprises buildings of a public character, such as city halls (Pl. XXXI), court-houses (Pl. XXXIX, *A*), asylums, public schoolhouses, etc., which were badly desibned and constructed or for the construction of which insufficient funds had been voted, so that the materials and workmanship, under imperfect inspection, or

worse, were of very poor quality. In contrast to such construction were the United States Government buildings—the mint and the appraisers' (or customs) building (Pl. XXVIII, A), in San Francisco, and the post-office building in Oakland—all of which were either entirely uninjured or very slightly injured by the earthquake. These buildings were well designed and constructed with the best materials and workmanship, upon foundations that had been tested and found strong and satisfactory. The results to both of these classes of buildings were fully to be expected.

As a second class of buildings that suffered badly may be grouped those of the oldest type of wooden structure in San Francisco, lightly resting upon slim wooden underpinning, which stood upon soft and unstable soil or loose, unconsolidated sand. Such houses went down at the first shock, as one would naturally expect. In contrast to these flimsy structures are the thousands of more substantially constructed wooden buildings that still stand intact, except as to chimneys and some plastering, all over the unburned part of the city. These structures were built fairly well and upon stable foundations; and the writer believes from his personal observation that no well-founded and well-constructed building of wood in San Francisco was injured to a greater degree than those just mentioned. In a country subject to earthquakes a strongly framed and well-founded wooden house, not exceeding three stories in height, with nondisintegrating plaster and finish, light tile chimneys, and ample fire prevention and protection, would seem to be the ideal type of residence structure.

Experience shows that buildings constructed with exterior brick walls laid in common mortar, with timber columns and girders, tied and braced little or not at all, constitute a third class of buildings which are nonresistant to a severe earthquake, particularly if they are erected upon a poor foundation. Even if the girders and columns are of metal, they are pulled apart, and the walls fall inward or outward during the shock. Only rich Portland cement, laid with wetted brick, and strong joists, ties, and anchorage, endured the stress.

The behavior of the high steel-frame office buildings, which constitute the fourth class, has shown that in order to resist perfectly the bending moments and shears induced by the swaying due to the earthquake movement, such buildings should be stiffened in their joints and connections by the best riveting combinations, and knee and other bracing, particularly at or near the ground floor. This requirement is of the utmost importance, and so also is the one that the swaying referred to should be diminished by the liberal introduction of diagonal and wind bracing throughout. The proper bracing in the lower stories has in some buildings been omitted, on the demand of

owner or lessee, to afford more glass or light space, but such design has a weakening effect, and should be discouraged. The Marston Building, on Kearney street, is an object lesson in this respect. On the other hand, the Whittell Building, on Geary street, near Union square, is commended for its deep plate girders and heavy steel generally. It stood well, and no rivets were sheared. Columns, exterior and interior, in steel-frame buildings, should in future be put in more liberally on the first and second stories, and the strongest joints and connections should be adopted in order to resist the bending and shearing. These improvements will greatly stiffen the steel frame, and prevent the cracking of the walls. The Kohl Building, thus stiffened by lattice girders on all floors, was uninjured in its exterior stonework and brickwork, although built upon the edge of the made ground along the old shore line. With such strengthening the high steel structures will safely endure an earthquake of even greater severity than that of April 18, 1906. This kind of building has proved its worth and reliability, and minor improvements, as advocated, will produce an enduring structure.

In a fifth class are to be placed, but not as failures, concrete and reenforced-concrete structures. These have become popular with a large number of designers in San Francisco, on account of the strength claimed for them, and on account of the indestructibility, facility of construction, and fire and rust protection that their materials afford. Unfortunately for San Francisco, there were very few structures of concrete or reenforced concrete in the city at the time of her great trial; but these few behaved well during both the earthquake and the resulting fire. Therefore, although such structures are admittedly new and comparatively experimental on the Pacific coast, the confidence reposed in them has already led to the designing and construction of a number of large buildings of this type for public or business purposes. At present the sentiment is to limit them to a height of six or eight stories, on account of their experimental character and because of the fear that greater height would permit a reversal of stress, due to earthquake and wind force in their reenforced girders. It is agreed that the columns should be reenforced with steel and braced together wherever possible; that the girders should be similarly reenforced for tension and shear, and made, so far as practicable, continuous over the columns; and also that the joints and connections should be strongly stiffened and the curtain walls strengthened by a reenforcement.

Mill construction with brick will undoubtedly be utilized in many buildings for a considerable time to come, but the lesson has been taught that the materials used should be first-class pressed brick, well wetted, and cement mortar, and that all parts should be thoroughly

tied and anchored together. San Francisco's experience has proved that this rule is a most important one to follow in all brick and stone construction, and its neglect in the past has resulted in much loss and ruin.

FIRE-FIGHTING APPARATUS AND FIRE-RESISTING MATERIALS.

The damage inflicted on San Francisco from the direct and immediate effects of the earthquake was relatively small, being estimated at only 3 to 10 per cent of the total loss; but a subsequent and indirect effect was to paralyze the water supply and its distributing system, start a great conflagration and render impossible its extinguishment with the means at hand, cause the death of at least 600 human beings, burn approximately $500,000,000 worth of property, render homeless and miserable 200,000 people, and inflict remoter damages to business, commerce, and labor, only to be estimated in the future. Inasmuch as it can be plainly seen, by looking backward, that nearly all of this destruction and suffering might have been prevented by wise foresight and provision, it is felt that a warning should be sent to all the cities in the world. Any city that disregards this warning will be guilty of a great crime.

San Francisco should have had separate and ample water mains entering the city on several independent lines from different sources of supply, and numerous distributing reservoirs on the hills in various parts of the city, always well filled, independent and yet with a distributing system meshing the entire area, with its pipes so joined or valved that they could be separated or united as desired. There should have been in that city, almost surrounded by salt water, a separate system of flexible salt-water mains for fire and sewer purposes, and numerous large cisterns in her streets, laid in reenforced concrete, with somewhat flexible lining and pipes. These cisterns, only a few blocks apart, should have been filled at all times with salt water. There should have been many wide streets—like Van Ness avenue, where the fire was finally checked—and many large squares, the city being thus divided into numerous fire districts. The fire department should have included a dynamiting corps of experienced fire fighters, and a number of fire boats always ready along the water front and among the shipping. None of these things did San Francisco have. With these means available, probably this story of the greatest fire in history would never have been written.

Of a building's entire fire risk, that from fire within the building is estimated, on the average, at 40 per cent, the other 60 per cent of the risk being from exterior fires. This risk for interior fires should

be reduced to a minimum by ample provision for fire prevention. As far as practicable, combustible material should be eliminated. Several of the fine so-called fireproof buildings in San Francisco were injured chiefly by the burning of their wooden trim, floors, doors, office furniture, papers, books, carpets, rugs, etc. Wooden floors have proved to be dangerous and objectionable; but in some places non-combustible wood may be used for them and for the interior trim, as, for example, where the heat could never be very great. Metal trim, doors, windows, sash, and casings, together with plate glass, or, better, wire glass, may confine a fire to a single room, preventing a general combustion. Adequate fire-extinguishing apparatus—such as fire hose, always connected with good water pressure, wells with automatic pumps, and tanks in the basement or upon the roof, with pipe connections—was lacking in nearly all of San Francisco's buildings, even in those of the highest class. In the California Electric Company's building the standpipes, with attached hose, the well, pump, and tank in the basement, and the roof tank, together with the metal sash and the wire-glass windows, proved the value of such a private system, saving that property from the hot fire around it, though every adjacent structure was burned. As this building was not fireproof, the value of the fire-extinguishing system can be well understood, and had all the large establishments been equally well equipped the conflagration would have been quickly checked and a vast amount of property saved. Automatic sprinklers connected with the above-mentioned plant will afford excellent fire protection within and will greatly reduce insurance rates.

While the fire danger from exterior fires to a given building is ordinarily estimated at 60 per cent, this risk practically becomes 100 per cent, of course, in a great conflagration. In San Francisco little protection from exterior fires had been adopted. There were few metal shutters or steel roller shutters, and most of those were of imperfect design, proving unsatisfactory when tested. The openings in walls were fatal points of weakness in all the great buildings. Wire-glass windows, though few in number, behaved well, but wooden instead of metal sashes were great sources of fiery contagion. Metal covering over wooden doors and window frames was generally inefficient. Ordinary glass was quickly cracked by heat from the exterior; the sashes took fire and the flames rushed in through the openings, consuming all combustible material within. Many of the best buildings were gutted in this manner. Had they been furnished with metallic shutters of the best design, with wire glass in metal sashes, and with cornice and other exterior sprinklers, supplied by a private water plant, they certainly might have been saved. Thus the employees of the United States mint (Pl. XXXVIII), with a

scanty private supply of water, made a desperate and gallant fight from the roof of the building and within, and saved it, little injured.

As most metallic shutters rapidly deteriorate with time, rust, and weather, and often become jammed so that they will not close, many architects prefer wire glass in hollow metallic sash and window sprinklers. This combination has proved effective.

San Francisco's experience indicates that wells and elevator shafts, running up through many stories, should be guarded by brick or reenforced-concrete walls, fitted with double metal rolling doors, bolted to the walls to allow for expansion, or with automatic sliding doors and wire-glass partitions. There was little or no provision for cutting off the draft of air that will ascend through such a shaft during a fire, and great destruction resulted in consequence. The Call Building took fire from the power house behind it, on the other side of Stevenson street, the heat being drawn through the tunnel to the elevator shaft, up which it rushed with the fierce draft given by the 18 stories, breaking glass and burning doors, furniture, trimmings, and office contents. The Telephone Building, on Bush street (Pl. XLI, *A*), met a similar fate, being consumed from within. This new structure was claimed to have the best fire protection in the city.

The importance and value of real protection will be appreciated when it is stated that a third-class building with a complete fire-prevention plant is insured for less than a first-class one that does not have it. This fact should be understood by all owners. Moreover, all parts of an establishment should be equally protected, for the fire may begin anywhere. The new Telephone Building was burned owing to the nonobservance of this rule, catching fire through the unprotected wooden back door of the basement. The structure was fitted with "tin-clad shutters" and wire glass on the side and rear openings and with steel rolling shutters in front. The fire broke through the rear wooden door into two well shafts and a corridor and, rushing upward, consumed every floor. The building was destroyed by a fire that entered through a single unprotected opening. The tin-clad shutters were destroyed and much of the wire glass was melted or broken by the hot fire. The rolling shutters in front still hung, but were bent so that the windows were exposed.

Concrete floors with metallic-mesh reenforcement are strongly recommended for strength and fireproof character. Noncombustible wooden floors, doors, and trim were installed in a few buildings, and under ordinary conditions would probably have limited the destruction to "one-room fires," but the heat was so high, and in general the bulk of papers, books, and furniture so great, that all were consumed. A noninflammable substitute for woodwork and trim generally is greatly to be desired.

Double windows of wire glass in hollow metallic frames are recommended, or where such material would be objectionable by cutting off the view, double plate glass is considered next best. Interior doors should be of metal, or at any rate metal covered, in fireproof buildings, and the light for corridors and halls should come through wire glass. As the installation of wire glass, metallic rolling shutters, and metal sash involves only a small percentage of the cost of the building, and as these materials have proved to be of such excellent service as fire protection when of the best quality and workmanship, a wise economy demands their use in every important fireproof building.

Capitalists and owners must understand that perfect fire protection for structural steel is necessarily expensive. Any so-called fireproofing that is cheap and flimsy is a delusion and will not serve. The application of an effective method insures permanence of the structure and at the same time greatly reduces the rates of insurance. Steel columns may be well fireproofed by surrounding them with the best quality of stone or cinder concrete 4 inches in thickness, or by 3 inches of either when hollow tiling is put on the exterior.

A 3-inch porous terra-cotta tiling, wrapped on the outside with wire, and with metal mesh used around the bed course of the column, has proved efficient. The mortar of the tiles should contain a large proportion of cement, and the tiles should be strongly anchored to the columns to prevent their falling away in earthquake or fire and so leaving the steel exposed.

In the great fire, decorations, trim, inflammable oil paints and varnishes, in office buildings, aided materially in spreading the flames. A noninflammable water-color paint that will endure washing has been recommended.

Fire walls of brick, extending above the roofs of buildings, were effective in resisting the spread of the fire; but the support derived from metal bands and anchors was neglected in many such walls, as in much other masonry in San Francisco; a large number of them fell, therefore, during both the earthquake and the fire, particularly those laid in common mortar. This was also a common fate of unsupported gables and towers. Walls that were well anchored, as in the Union Trust Building, remained in perfect condition.

Cast-iron columns in some buildings endured the earthquake and the fire fairly well, but undoubtedly would have been broken or shattered had cold water been thrown upon them in the midst of the great heat. They should no longer be used, for at present they cost more than steel for an equal factor of safety, and their connections are clumsy and weak.

Structures made of concrete blocks were as a rule greatly damaged

or even ruined by the earthquake, owing to imperfect anchorage and failure to cohere at their joints (Pl. XVII, *A*).

Granite, sandstone, and marble were badly cracked and spalled by the fire, much of the marble crumbling to powder. The granite piers in the front of the Hobart Building were nearly all chipped away, and they are now reenforced by new temporary supports.

Chemical fire extinguishers were effectively used immediately after the earthquake in some of the uptown residences, thereby preventing an increase in the number of fire centers at the beginning of the conflagration. It is possible that numerous chemical engines and locally installed chemical extinguishing plants in the downtown districts might have greatly limited the spread of the flames, despite the dearth of water.

FINAL CONCLUSIONS.

EARTHQUAKE PROTECTION.

A proper foundation, stable and firm, is of vital importance, and particularly on soft, marshy, or made ground (Pls. XLIII, *B*; XLIV, *A*). Anchoring, bonding, and tying should be practiced with exactness in all masonry. Steel framing should be made heavier rather than lighter, and joints, connections, bracing, and flooring should be strongly united. Girders and columns should be made very stiff and, where practicable, continuous.

FIRE PROTECTION.

The lessons taught by the great fires of Boston, Chicago, and Baltimore have been verified by San Francisco's experience.

Fireproofing should be of the most perfect type, and no reasonable expense should be spared in its installation.

Roofs, roof appurtenances, and skylights should be given ample protection against fires from without. A great excess of fire hose and apparatus, beyond ordinary needs, should be available. A strong bond for fireproof tiling, etc., for both girder and column protection, is essential. Protection for front windows, as well as for side and rear ones, is of vital importance. Good protection for steel frames and steel roof trusses in attics or other exposed or unusual places should be provided. Liberal use should be made of fire retardant in windows, doors, transoms, etc. Wise and liberal use of concrete and reenforced concrete for girder and column fireproofing has proved its saving quality. Interior fire protection and prevention by wells, pumps, sprinklers, and water tanks vastly lessen fire risk.

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INDEX.

T.

CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 324.]

The publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists can be had on application.

Most of the above publications can be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they can be obtained, free of charge (except classes 2, 7, and 8), on application.
2. A certain number are delivered to Senators and Representatives in Congress for distribution.
3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they can be had at prices slightly above cost.
4. Copies of all Government publications are furnished to the principal public libraries in the large cities throughout the United States, where they can be consulted by those interested.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports; Q, Fuels; R, Structural materials. This paper is the first in Series R and bears the following title (B=Bulletin):

SERIES R, STRUCTURAL MATERIALS.

B 324. The San Francisco earthquake and fire of April 18, 1906, and their effects on structures and structural materials; reports by G. K. Gilbert, R. L. Humphrey, J. S. Sewell, and Frank Soulé, with preface by J. A. Holmes. 1907. 170 pp., 57 pls.

Correspondence should be addressed to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

AUGUST, 1907.

A. ROAD CROSSING FAULT TRACE NEAR POINT REYES STATION.

Looking southwest. Offset, 20 feet. Photograph by G. K. Gilbert.

B. FENCE PARTED BY EARTHQUAKE FAULT.

The fault trace or fracture accompanying the earthquake is inconspicuous, although the horizontal displacement is considerable. Photograph by G. K. Gilbert.

EARTHQUAKE EFFECTS ALONG THE FAULT TRACE.

REDWOOD TREE 6 FEET IN DIAMETER ON LINE OF FAULT SOUTH OF FORT ROSS.

The tree was split to a height of 35 feet, although the horizontal displacement was slight. The opening is wedge-shaped at the base, running from a width of 8 inches on the side shown to a fine crack on the farther side. Photograph by Richard L. Humphrey.

A

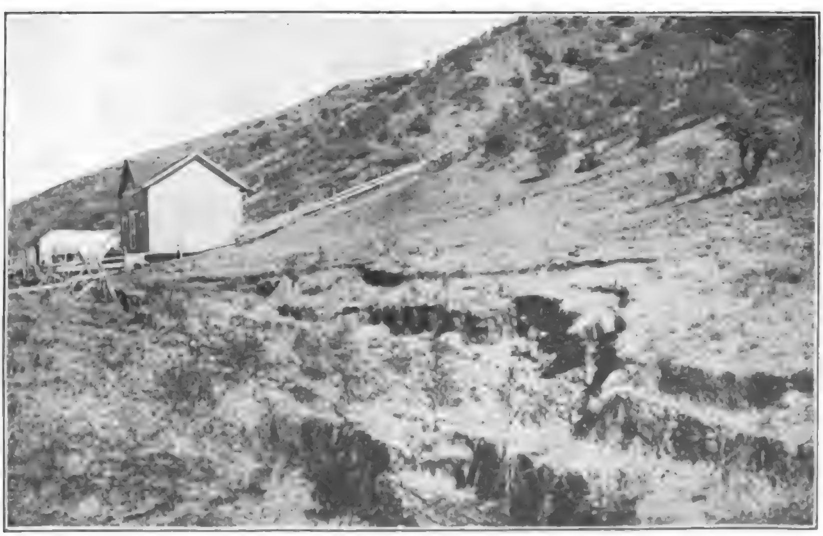
B

THE FAULT TRACE NEAR POINT REYES STATION.

A, Looking northwest; *B*, Looking southeast. Photographs by G. K. Gilbert.

A. SECONDARY CRACKS, SHORE OF BOLINAS LAGOON.

Photograph by G. K. Gilbert.



B. SECONDARY CRACKS, WITH SETTLING, BOLINAS.

Photograph by G. K. Gilbert.

RESULTS OF EARTH FLOW, NINTH STREET, SAN FRANCISCO.

Photograph by G. K. Gilbert.

A. SETTLING (5 FEET) ON DORE STREET, BETWEEN BRYANT AND BRANNAN STREETS, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. BUCKLING CAUSED BY EARTH FLOW, HOWARD STREET, SAN FRANCISCO.

Photograph by G. K. Gilbert.

EARTHQUAKE EFFECTS ON MADE GROUND.

A

B

SHIFTED BOTTOM OF TOMALES BAY.

A. General view; *B*. Edge of new shoal. Photographs by G. K. Gilbert.

A. EARTHQUAKE RIDGES ON TIDAL FLAT, TOMALES BAY.

Photograph by G. K. Gilbert.

B. SLIPPING OF ALLUVIAL SOIL TOWARD SALINAS RIVER.

Grain field adjoining road along river between Spreckels's sugar mill and Salinas. Photograph by A. C Lawson.

A

B

DAMAGE TO PILARCITOS 30-INCH PIPE LINE BY EARTHQUAKE.

A, Offset; *B*, Telescoping. Photographs submitted by Frank Soulé.

A. COLLAPSED PILARCITOS 30-INCH WROUGHT-IRON PIPE LINE, NEAR TRESTLE CROSSING THE FAULT.

The slip produced a compression on the pipe line which buckled it, thereby throwing down the trestle support. The consequent parting of the pipe line suddenly released the water from the pipe, causing a vacuum which brought about the collapse. Photograph by Richard L. Humphrey.

B. HOUSE ON LINE OF FAULT, TORN ASUNDER BY EARTHQUAKE.

Near Wrights Station, on Southern Pacific Railroad. Photograph by Richard L. Humphrey.

A. RACKING AND SPALLING OF CONCRETE PIER DUE TO EARTHQUAKE.

Near south abutment of Southern Pacific Railroad bridge over Pajaro River. Photograph by Richard L. Humphrey.

B. ENDURANCE OF CONCRETE DAM NEAR FAULT TRACE, AT CRYSTAL SPRINGS LAKE, SAN MATEO.

Photograph by Richard L. Humphrey.

A. EFFECT OF EARTHQUAKE ON THE END AND THE INSUFFICIENTLY BRACED CENTRAL PORTION OF A BRICK BUILDING, SPRECKELS'S SUGAR MILL, ABOUT 4 MILES SOUTH OF SALINAS.

Note the stripping of brick pilasters from steel columns. Photograph by Richard L. Humphrey.

B. EARTHQUAKE WRECK OF NEW HALL OF JUSTICE, SAN JOSE, BUILT ON ALLUVIAL SOIL.

Wreck due to poor quality of stonework and unnecessarily massive construction. Photograph by Frank Soulé.

A. COMPARATIVE EARTHQUAKE ENDURANCE OF DISSIMILAR STRUCTURES, AGNEW INSANE ASYLUM, NEAR SAN JOSE.

Tanks on steel trestle, undamaged, and circular brick stack, collapsed. Photograph by Richard L. Humphrey.

B. EARTHQUAKE EFFECT, HIGH SCHOOL BUILDING, SAN JOSE.

Photograph submitted by Frank Soule.

A. COMPARATIVE BEHAVIOR OF REENFORCED CONCRETE AND BRICKWORK UNDER EARTHQUAKE VIBRATION, MUSEUM, LELAND STANFORD JUNIOR UNIVERSITY.

The central portion, of reenforced concrete, was undamaged, but the brick wings collapsed. Photograph by Richard L. Humphrey.

B. COMPLETE WRECK BY EARTHQUAKE, COURT-HOUSE AND HALL OF RECORDS, SANTA ROSA.

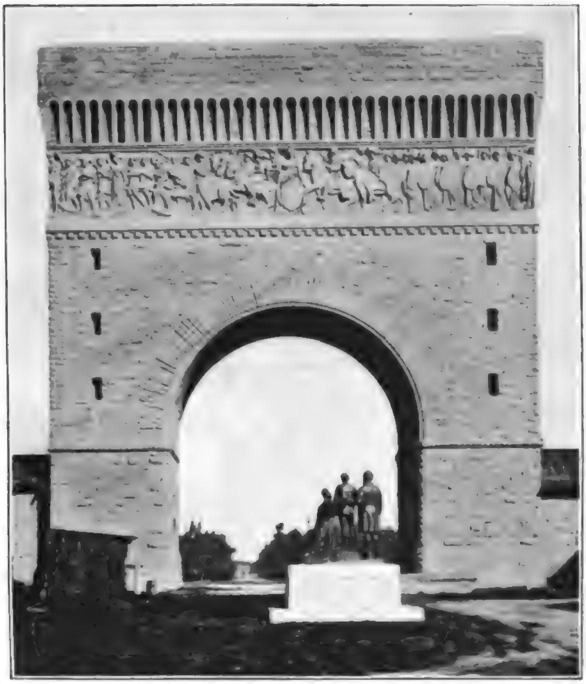
Wreck due to light wooden framing, insufficient bracing, and poor mortar. Photograph submitted by Richard L. Humphrey.

A. UNDAMAGED STEEL FRAMEWORK SUPPORTING DOME OF LIBRARY.

B. COLLAPSE OF BRICK WALLS, CAUSING DESTRUCTION OF STEEL SKELETON DOME OF GYMNASIUM.

ENDURANCE OF STEEL FRAMEWORK AS AFFECTED BY METHOD OF SUPPORT, LELAND STANFORD JUNIOR UNIVERSITY.

Photographs by Richard L. Humphrey.



A

B

MEMORIAL ARCH, LELAND STANFORD JUNIOR UNIVERSITY.

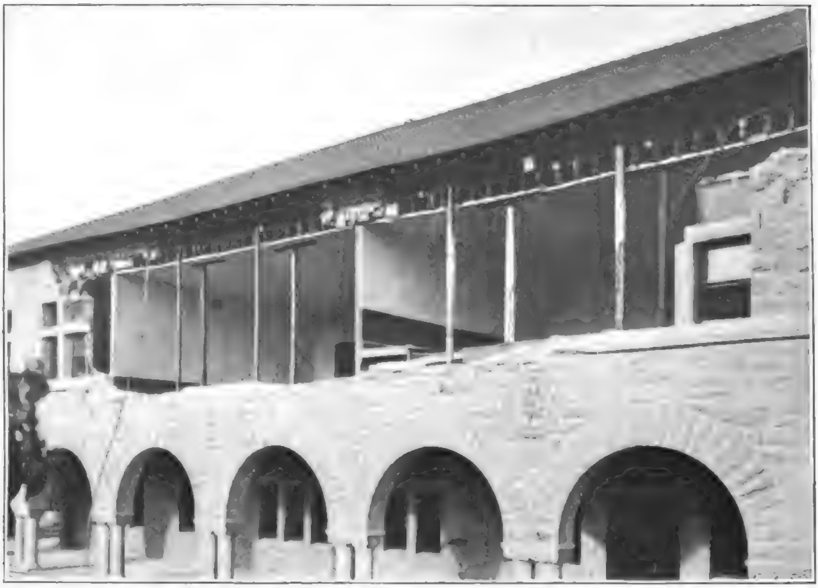
A, Before the earthquake (photograph submitted by Richard L. Humphrey); *B*, Earthquake effect (photograph by Richard L. Humphrey). The beams designed to stiffen the walls were not tied to them and helped to batter them down when the shock came.

A. COLLAPSE DUE TO LACK OF TIE BETWEEN WALLS AND FRAME, THIELE BUILDING (CEMENT BLOCK), PALO ALTO.

Photograph by Richard L. Humphrey.

B. COLLAPSED TOWER AND GENERAL EARTHQUAKE WRECKAGE, MEMORIAL CHURCH, LELAND STANFORD JUNIOR UNIVERSITY.

Photograph by Richard L. Humphrey.



A. EARTHQUAKE DAMAGE DUE TO LACK OF TIE AND BRACING, GEOLOGICAL DEPARTMENT, LELAND STANFORD JUNIOR UNIVERSITY.

Photograpn by Richard L. Humphrey

B. EARTHQUAKE EFFECT ON ARCHES. LELAND STANFORD JUNIOR UNIVERSITY.

Spalling of caps and movement of upper part of columns. Photograph by Richard L. Humpnrey.

A. ENDURANCE OF WALLS TIED TOGETHER WITH STEEL RODS, LEE BROTHERS' WAREHOUSE, SANTA ROSA.

Slightly damaged at cornice. The few blocks which were thrown down by the earthquake were replaced previous to the taking of the photograph.

B. WALL THROWN DOWN BY EARTHQUAKE VIBRATIONS OF ROOF TRUSSES WHICH WERE NOT TIED TO WALL, VANDERVOORT BROTHERS' LIVERY, PALO ALTO.

EARTHQUAKE EFFECTS ON CEMENT-BLOCK WALLS.

Photographs by Richard L. Humphrey.

A. LOOSENING OF ARCH STONES AND SPALLING OF COLUMNS BY EARTHQUAKE, FRANCIS SCOTT KEY MONUMENT, GOLDEN GATE PARK, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. UNDAMAGED REENFORCED-CONCRETE STRUCTURE AT MILLS COLLEGE, NEAR OAKLAND.

Bell tower, within a few feet of a brick building that was badly racked by the earthquake. Photograph by Richard L. Humphrey.

A. RACKING OF NEWLY CONSTRUCTED BUILDING, SYNAGOGUE, GEARY AND FILLMORE STREETS, SAN FRANCISCO.

Note the separation of the brick veneer from the backing; also the racking of the wall at the corner. Photograph by John Stephen Sewell.

B. GOOD EARTHQUAKE ENDURANCE OF BUTTRESSED WALLS, SYNAGOGUE EMANUEL, SAN FRANCISCO.

Photograph submitted by Richard L. Humphrey.

A. X CRACKS IN BRICKWORK, CAUSED BY ROCKING, HOUSE IN SAN FRANCISCO.

Photograph submitted by Richard L. Humphrey.

B. SLIP OF FOUNDATION OF CYCLORAMA, STRAWBERRY HILL, GOLDEN GATE PARK, SAN FRANCISCO, CAUSING COLLAPSE OF THE STRUCTURE.

Photograph by Richard L. Humphrey.

A. EARTHQUAKE EFFECT ON STRUCTURE OF REENFORCED CONCRETE OF POOR QUALITY.

Cyclorama, Strawberry Hill, Golden Gate Park, San Francisco. Photograph by Richard L. Humphrey.

B. EFFECT OF EARTHQUAKE ON ADJACENT BUILDINGS OF DISSIMILAR TYPE AND CONSTRUCTION.

Old Mission Dolores, San Francisco, undamaged. Tower of new church adjoining was so badly damaged that it had to be taken down. Photograph by Richard L. Humphrey

A. FAILURE OF CAST-IRON SHELL OF CONCRETE-FILLED CAST-IRON COLUMN BY FIRE, ACADEMY OF SCIENCES BUILDING, SAN FRANCISCO.

The concrete core supports the load. Note also the effect of the earthquake on the brick wall in the rear. Photograph by Richard L. Humphrey.

B. SPALLED GRANITE, MARKET STREET ENTRANCE OF ÆTNA BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. SUBSIDENCE OF STREET IN FRONT OF ÆTNA BUILDING, SAN FRANCISCO.

Photograph by John Stephen Sewell

B. FIRE ENDURANCE OF CONCRETE, ANNEX OF ACADEMY OF SCIENCES BUILDING, SAN FRANCISCO.

Reenforced-concrete floors and concrete-filled cast-iron columns with plaster covering. Photograph by Richard L. Humphrey.

A. BUCKLED COLUMNS AND COLLAPSED FLOOR PANEL, BULLOCK & JONES BUILDING, SAN FRANCISCO.

Photograph by John Stephen Sewell.

B. INCIPIENT FAILURE OF NAKED CAST-IRON COLUMN IN CITY HALL, SAN FRANCISCO.

Ceiling on the point of falling. Photograph by John Stephen Sewell.

A. EARTHQUAKE ENDURANCE OF REENFORCED-CONCRETE BUILDING, BEKINS VAN AND STORAGE COMPANY'S WAREHOUSE, SAN FRANCISCO, UNDER CONSTRUCTION.

The only building of pure reenforced-concrete type in the city. The brick walls composing the shell of the building were cracked, but the reenforced-concrete floors and columns were uninjured. Photograph by Richard L. Humphrey.

B. FAILURE OF TERRA-COTTA COLUMN COVERINGS, RESULTING IN BUCKLED COLUMNS; ENDURANCE OF CINDER-CONCRETE FLOORS; CENTER OF GROUND FLOOR, ARONSON BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. EARTHQUAKE ENDURANCE OF A WELL-CONSTRUCTED BRICK BUILDING: APPRAISERS' WAREHOUSE, SAN FRANCISCO.

The walls were built with full-header courses and show only a few slight cracks, although the building was located on alluvial soil. Photograph by Richard L. Humphrey.

B. FAILURE OF ORNAMENTAL TERRA COTTA, CROCKER ESTATE BUILDING, SAN FRANCISCO.

This terra cotta failed though solidly filled with brick mortar. The damage shown was probably due to fire, although damage of this kind was caused by both earthquake and fire. Photograph by John Stephen Sewell.

A. EARTHQUAKE CRACKS IN WALL OF VAULT, CALIFORNIA CASKET COMPANY'S BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. COLLAPSE OF FLOOR PANEL, CAUSED BY LOAD FALLING FROM A FLOOR ABOVE, THIRD FLOOR OF ÆTNA BUILDING, SAN FRANCISCO.

The failure of the upper floor was due to the softening by heat of reenforcing steel bands. Photographs by Richard L. Humphrey.

A. EARTHQUAKE DAMAGE MINIMIZED BY SPECIAL CONSTRUCTION, DEWEY MONUMENT, SAN FRANCISCO.

The drums on the shaft were displaced slightly, but were kept from falling by a steel core. Photograph by John Stephen Sewell.

B. X CRACKS IN WALLS, DUE TO ROCKING OF BUILDING BY EARTHQUAKE, CHRONICLE BUILDING AND ANNEX, SAN FRANCISCO, LOOKING EAST.

The Palace Hotel (at the right) was completely gutted by fire, but the walls remained in good condition. Photograph by Richard L. Humphrey.

RUIN OF THE $7,000,000 CITY HALL, SAN FRANCISCO, BY EARTHQUAKE AND FIRE.

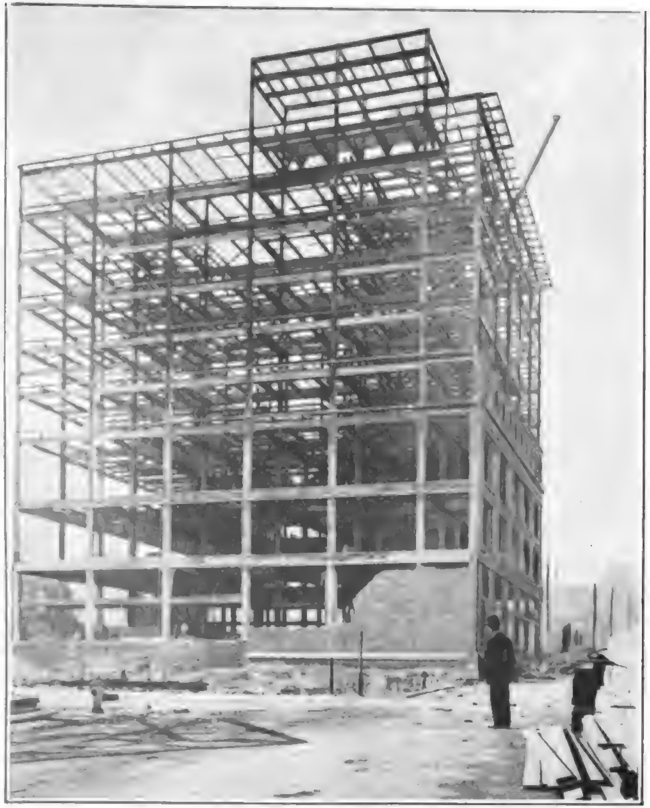
Photograph submitted by Frank Soulé.

A

B

COMPLETE FAILURE OF SLOW-BURNING WOOD CONSTRUCTION, THE EMPORIUM, SAN FRANCISCO.

A large department store. *A*, Interior (photograph by John Stephen Sewell); *B*, Exterior (photograph by Richard L. Humphrey).



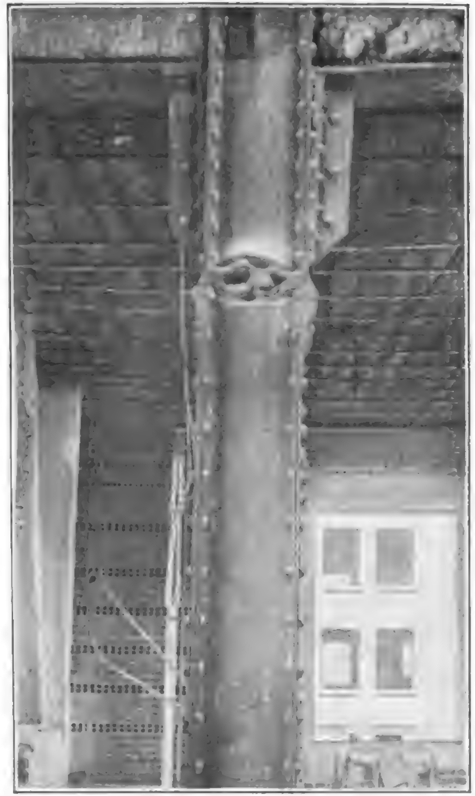
A. BEHAVIOR OF STEEL FRAME, BUTLER BUILDING (INCOMPLETE), AT THE SOUTHWEST CORNER OF GEARY AND STOCKTON STREETS, SAN FRANCISCO.

Walls taken down in places because of earthquake damage, although damage to steel by earthquake and fire was nominal. Photograph by John Stephen Sewell.

B. EARTHQUAKE DAMAGE TO STONE PIERS, JAMES FLOOD BUILDING, SAN FRANCISCO.

Photograph by John Stephen Sewell.

A



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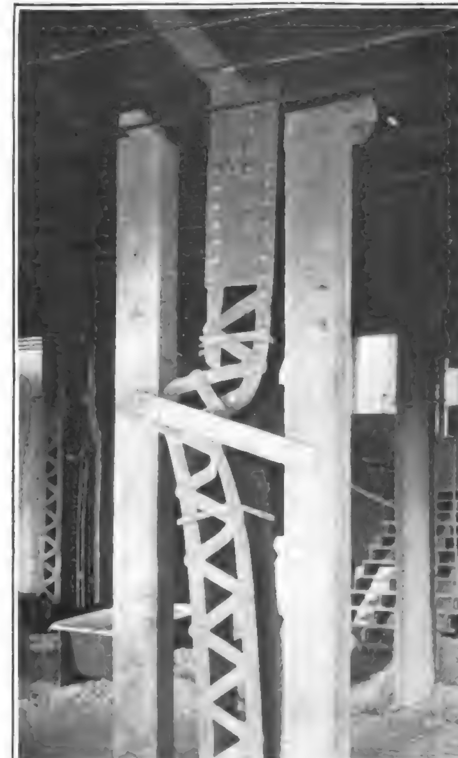
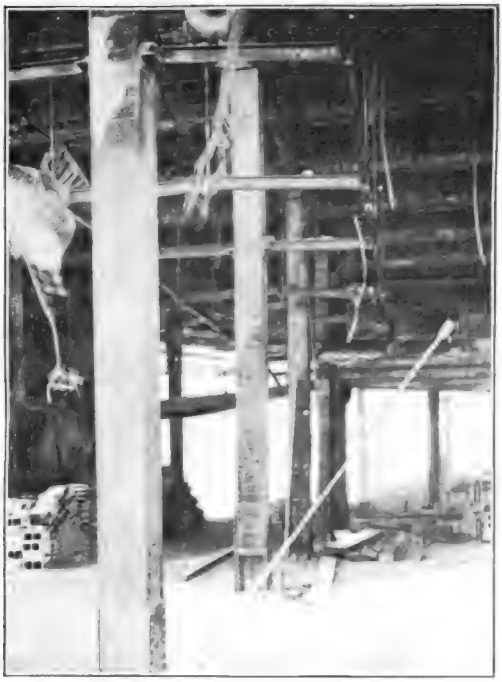


C

BUCKLING OF COLUMNS DUE TO FAILURE OF PLASTERED METAL-LATH FIREPROOFING, FAIRMOUNT HOTEL, SAN FRANCISCO.

The method of fireproofing was to inclose the column between the metal lath forming the partitions. Photographs by Richard L. Humphrey.



A. INCIPIENT BUCKLING OF COLUMNS FROM HEAT, FIRST STORY, JAMES FLOOD BUILDING, SAN FRANCISCO.

The brick filling probably saved the columns from fatal buckling or collapse. Photograph by John Stephen Sewell.

B. FAILURE OF SUSPENDED CEILING, HALL OF JUSTICE, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. GRANITE COLUMNS SPALLED BY FIRE, HOBART BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey

B. BUCKLING OF COLUMNS DUE TO FAILURE OF WIRE-MESH-AND-PLASTER FIREPROOFING, HOTEL HAMILTON, SAN FRANCISCO.

The fireproofing on either side shows the general condition in which it was left by the fire. It was stripped away from the column just before the photograph was taken in order to show the buckling. Photograph by A. L. A. Himmelwright.

A. STONEWORK SPALLED BY FIRE, HIBERNIA SAVINGS AND LOAN SOCIETY'S BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. EARTHQUAKE DAMAGE, JACKSON BREWING COMPANY'S BUILDING, SAN FRANCISCO.

Light walls, badly bonded and laid up with poor lime mortar, and flimsily constructed steel work. Photograph by Richard L. Humphrey.

A. GOOD EARTHQUAKE ENDURANCE OF A BUILDING OF THE MONUMENTAL TYPE: UNITED STATES MINT, SAN FRANCISCO.

Showing only slight damage to brick stack, probably due to earthquake. Photograph by John Stephen Sewell.

B. SPALLING OF STONEWORK BY FIRE, NORTHWEST FRONT OF UNITED STATES MINT.

Photograph by Richard L. Humphrey.

A. WRECKED TOWER AND SPALLED STONEWORK, HALL OF JUSTICE, SAN FRANCISCO.

Photograph by John Stephen Sewell.

B. COMPLETE WRECK BY EARTHQUAKE, DUE TO POOR DESIGN, MAJESTIC THEATER, SAN FRANCISCO.

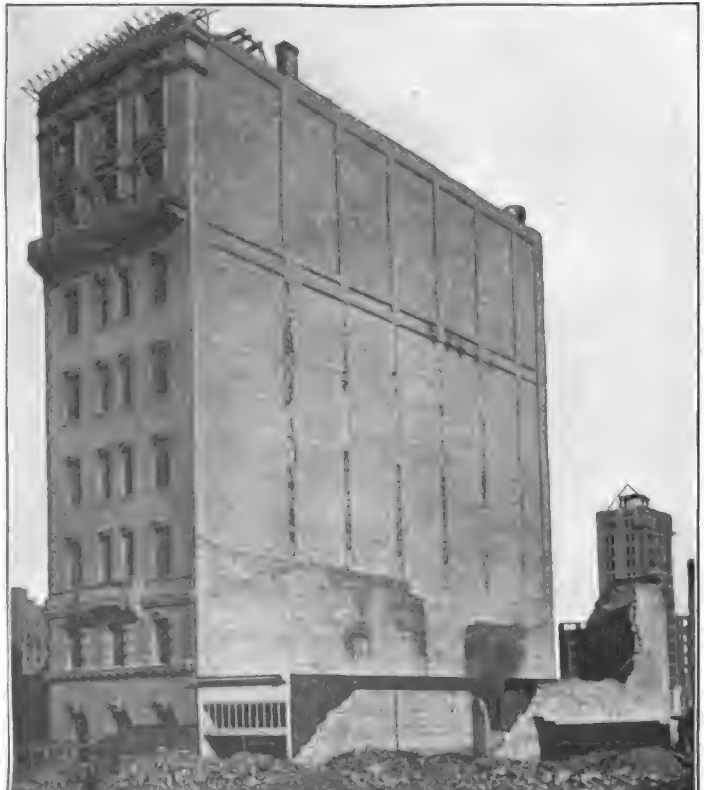
Photograph by Richard L. Humphrey.

A. SPALLING OF ENAMELED BRICK IN LIGHT WELL, AND FAILURE OF FIREPROOFING OF WINDOW-FRAME SEPARATORS, MERCHANTS' EXCHANGE BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. BUCKLING OF BASEMENT COLUMN DUE TO FAILURE OF TERRA-COTTA COVERING IN FIRE, MILLS BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.



A. ENDURANCE OF A WELL-PROTECTED BUILDING SUBJECTED TO SEVERE HEAT, MAIN EXCHANGE OF PACIFIC STATES TELEPHONE AND TELEGRAPH COMPANY, SAN FRANCISCO.

Rolling shutters, self-supporting brick walls, concrete floors, and concrete protection for columns and girders. Photograpn by Richard L. Humphrey.

B. WARPING OF PLASTERED METAL-LATH COVERING BY FIRE, MURPHY BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. ROOF TRUSSES DAMAGED BY HEAT THROUGH FAILURE OF TERRA-COTTA COVERING, MUTUAL LIFE BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. EFFECT OF SETTLING OF GROUND SUBJECTED TO EARTHQUAKE VIBRATIONS, STEEL-FRAME BUILDING UNDER CONSTRUCTION.

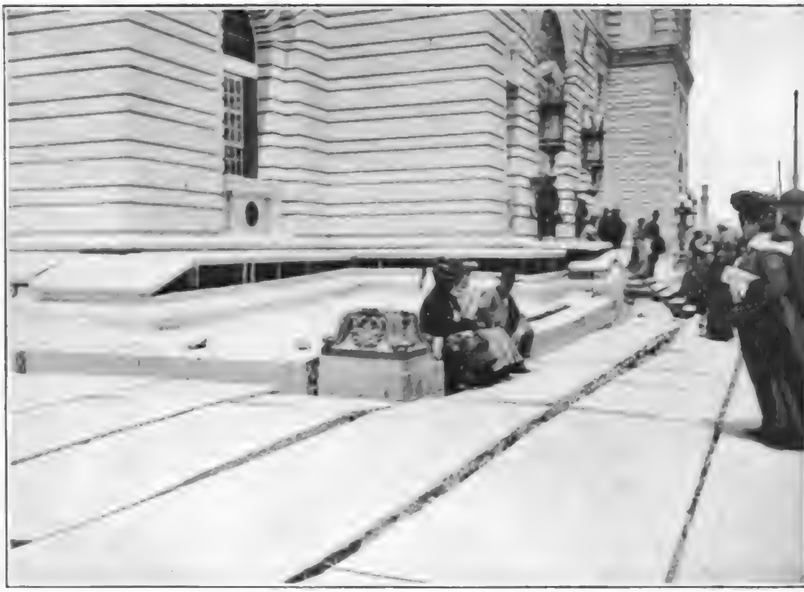
The concrete basement walls were not reenforced. Post-office in the background. Photograph by Richard L. Humphrey.

A. CRACKS IN MASONRY, PAVILION OF POST-OFFICE, SAN FRANCISCO.

The window reveal and sill were jostled together by the earthquake at the point indicated by the arrow. Photograph by John Stephen Sewell.

B. EFFECT OF SLIP, MISSION STREET, SAN FRANCISCO.

Corner of post-office building at the left. Photograph submitted by Richard L. Humphrey.



A. CRACKS IN MASONRY AND SETTLING OF OUTER TERRACE, POST-OFFICE BUILDING, SAN FRANCISCO.

The surface of the street went down at this point at least 4 feet. Photograph by John Stephen Sewell.

B. EFFECT OF EARTHQUAKE IN LOOSENING STONEWORK, NORTHEAST FACE OF POST-OFFICE BUILDING

Photograph by Richard L. Humphrey.

A

B

FAILURE OF HOLLOW TERRA-COTTA TILE FIREPROOFING.

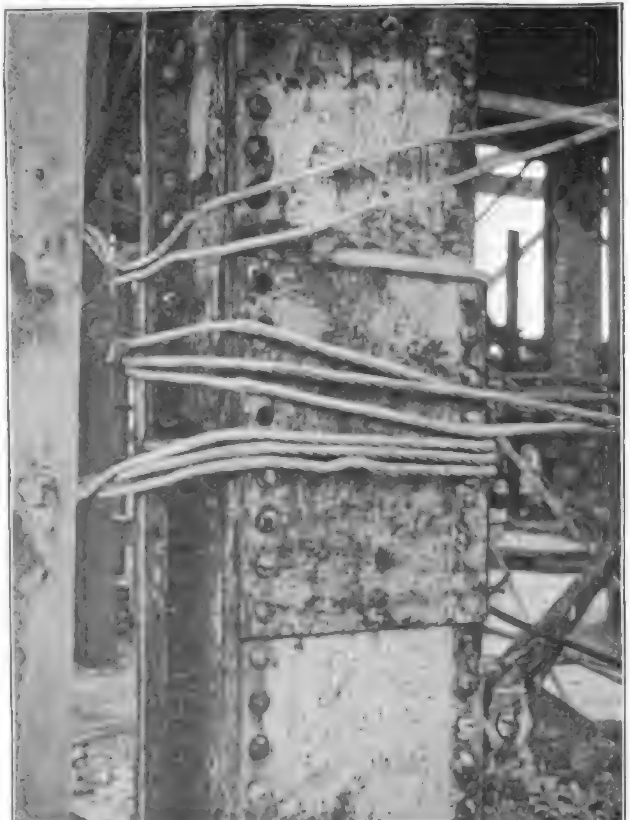
A, First story of Spring Valley Water Company's Building, San Francisco (photograph by John Stephen Sewell); *B*, Mills Building, San Francisco (photograph by Richard L. Humphrey). The lower webs of the floor tiles were spalled or taken entirely off by the fire.

A. BRICKWORK THROWN DOWN BY EARTHQUAKE VIBRATION, TOWER OF UNION FERRY BUILDING, SAN FRANCISCO.

Note bending of time-ball shaft Photograph submitted by Richard L. Humphrey.

B. EFFECT OF SEVERE SHAKING ON WELL-BONDED BRICKWORK FILLED WITH GOOD MORTAR, TOWER OF UNION FERRY BUILDING.

Note sagged tie-rod, stretched by the racking of the structure. Photograph by John Stephen Sewell.



A

B

SHEARED RIVETS, TOWER OF UNION FERRY BUILDING, SAN FRANCISCO.

A, In column cover plate; *B*, In diagonal connection. Photographs by Richard L. Humphrey.

A. BUCKLING OF BASEMENT COLUMN DUE TO FAILURE OF PLASTERED METAL-LATH FIREPROOFING, RIALTO BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey

B. DAMAGE SAID TO HAVE BEEN CAUSED BY DYNAMITE, RIALTO BUILDING.

Photograph by John Stephen Sewell.

A. FAILURE OF BASEMENT COLUMN DUE TO FIRE, SLOANE BUILDING, SAN FRANCISCO.

Photograph by John Stephen Sewell.

B. FAILURE OF TERRA-COTTA TILING AND METAL-FRAME WIRE-GLASS WINDOWS BY FIRE, LIGHT-WELL COLUMN, WELLS-FARGO BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. COLLAPSE OF BUILDING DUE TO BUCKLING OF COLUMNS, SPRING VALLEY WATER COMPANY'S BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. FAILURE OF TERRA-COTTA TILE COVERING IN FIRE, UNION TRUST COMPANY'S BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. AN UNFINISHED STEEL SKELETON, WITH NONFIREPROOFED STEEL WORK.

B. UNPROTECTED STEEL FRAME AND GENERAL FLIMSY CONSTRUCTION, COWELL BUILDING.

EFFECTS OF HEAT ON STEEL WORK, SAN FRANCISCO.

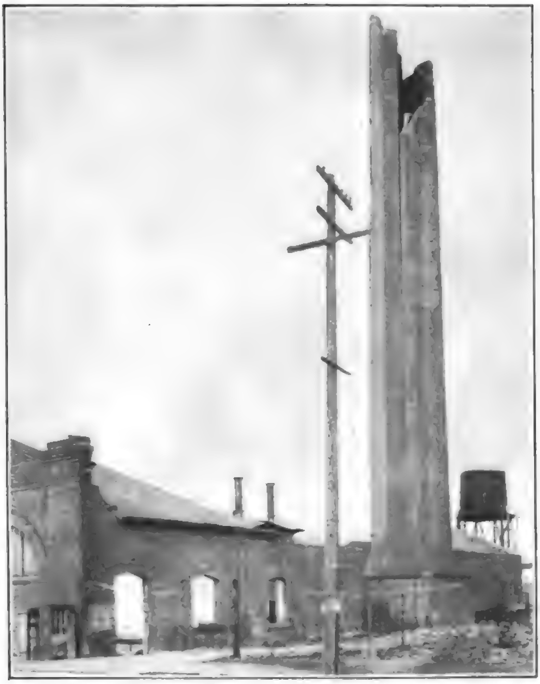
Photographs by Richard L. Humphrey.

A. ENDURANCE OF BRICK VAULT.

This vault, which was in the original Wells-Fargo Building, San Francisco, passed the fire test satisfactorily, although the building was completely destroyed. Note the defective steel "fireproof" safes near by. Photograph by Richard L. Humphrey.

B. ABSOLUTE FAILURE OF SO-CALLED "FIREPROOF" SAFES

In the rear are the Palace Hotel (at the left) and the Crocker Building (at the right). Photograph by Richard L. Humphrey



A. EARTHQUAKE DAMAGE TO BRICK STACK OF STAR SECTION, VALENCIA STREET POWER STATION, SAN FRANCISCO.

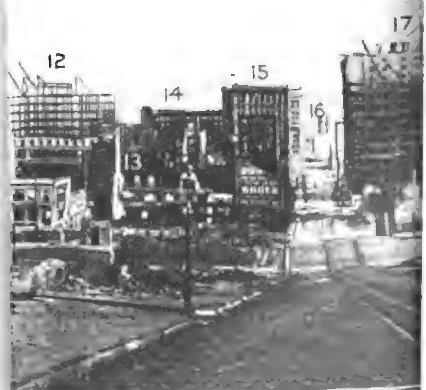
Showing peculiar crack in reentrant angle. Photograph by Richard L. Humphrey.

B. GENERAL EARTHQUAKE EFFECT ON FRAME BUILDINGS SITUATED ON ALLUVIAL SOIL, HOWARD STREET, SAN FRANCISCO.

Photograph by A. C. Lawson

DESTRUCTION BY FIRE, SAN FRANCISCO.

View looking west from Telegraph Hill, showing unburned houses on summit of Russian Hill. St. Francis Roman Catholic Church, with its excellent brick walls, in the foreground. Photograph submitted by Frank Soulé.

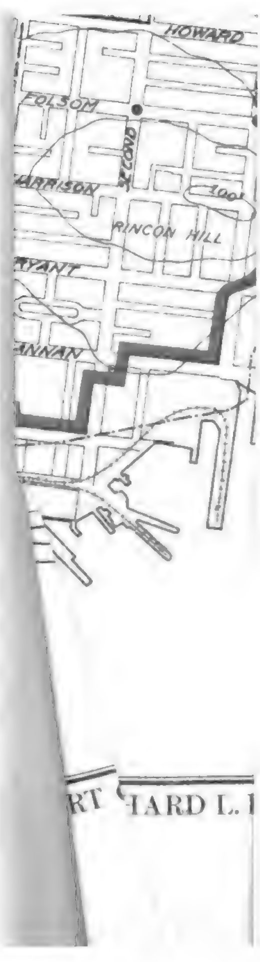


ANCISCO.

he area south of Pine street. Photograp

. Shreve Building.
. Call Building
. Synagogue Emanuel.
. Butler Building.

13. Dewey monumer
14. Emporium
15. James Flood Bu
16. Powell street, loc


HOWARD
FOLSOM
RINCON HILL